Effects of Drought in Central and South Texas

By H. E. THOMAS *and* others

DROUGHT IN THE SOUTHWEST, 1942-56

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[Plates are in pocket]

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By H. E. THOMAS and others

ABSTRACT

The effects of drought upon ground-water storage and discharge, and upon streamflow, vary tremendously in the central third of Texas (the area from the Panhandle to the Gulf of Mexico). Extremes are represented by (a) the Llano Estacado, where the drought had negligible effect upon ground-water resources, which are being progressively depleted by pumping for irrigation; and (b) the Balcones fault-zone aquifer west of San Antonio, whose storage and natural discharge declined substantially during the drought, but increased even more rapidly during succeeding years of more abundant precipitation.

INTRODUCTION

This chapter, the third in the report on drought in the Southwest, describes the effects of drought upon the ground-water storage and discharge and upon streamflow in the central third of Texas—the area from the Panhandle to the Gulf of Mexico (fig. 1). Subsequent chapters describe effects of the drought in other areas in the Southwest. The effects of drought are discriminated from water shortages due to other causes wherever possible.

The patterns of land and water resources in central and south Texas have many features in common with those of other Plains States (for example, Oklahoma and Kansas) and different from those of the States to the west (New Mexico, Colorado, Arizona, Utah, Nevada, and California). In all the States mentioned the population is concentrated at the lower altitudes, and the higher lands have relatively low population density. The mountains and plateaus of the six States west of Texas are very sparsely inhabited and have remained for the most part in public ownership. By contrast, the higher plains of Texas are of agricultural importance comparable with those at lower altitudes.

Superposed upon this contrasting pattern of land utilization is a comparable contrast in the water-resource pattern. In the States west of Texas the scenic but relatively uninhabited mountains and plateaus receive the most precipitation and are the chief water-producing areas. The people in those States may differ in their ideas as to the most effective way of obtaining the greatest yield from these producing areas, but they are in practically unanimous agreement that this yield should be used in the water-deficient lowlands, where they live. By contrast, Texas' pattern of precipitation is such that the lower lands to the southeast produce the greatest runoff per square mile, and the streams draining the higher lands to the north and west are more likely to be small and ephemeral. Needless to say, the inhabitants and landowners of these semiarid uplands would like to hold back this small runoff for use as a supplement or alternative to inadequate rainfall; and their interests thus come in conflict with those of people downstream, who also could utilize surplus runoff especially in time of drought. Thus there may be even greater controversy over specific programs of water conservation and development in Texas than one would expect to find in the more arid regions farther west.

Texas presents opportunities for hydrologic subdivision on the basis of precipitation, streamflow, or ground-water reservoirs. Precipitation is least in the west and progressively greater toward the east; it ranges from an average of less than 10 inches a year near El Paso to more than 50 inches annually in the southeast corner along the Gulf of Mexico. By contrast with other drought-ridden States of the Southwest, where precipitation is ordinarily greatest in the highlands and least in the lowlands, Texas receives its greatest rainfall on lands in the southeastern part of the State near sea level, and progressively less upon the higher plains to the west. The lines of equal rainfall (isohyets) run generally north and south across Texas, and the boundary between arid and humid regions is also approximately a north-south line, through Fort Worth, Waco, and the mouth of the Guadalupe River. This report is concerned with drought in the region west of that line.

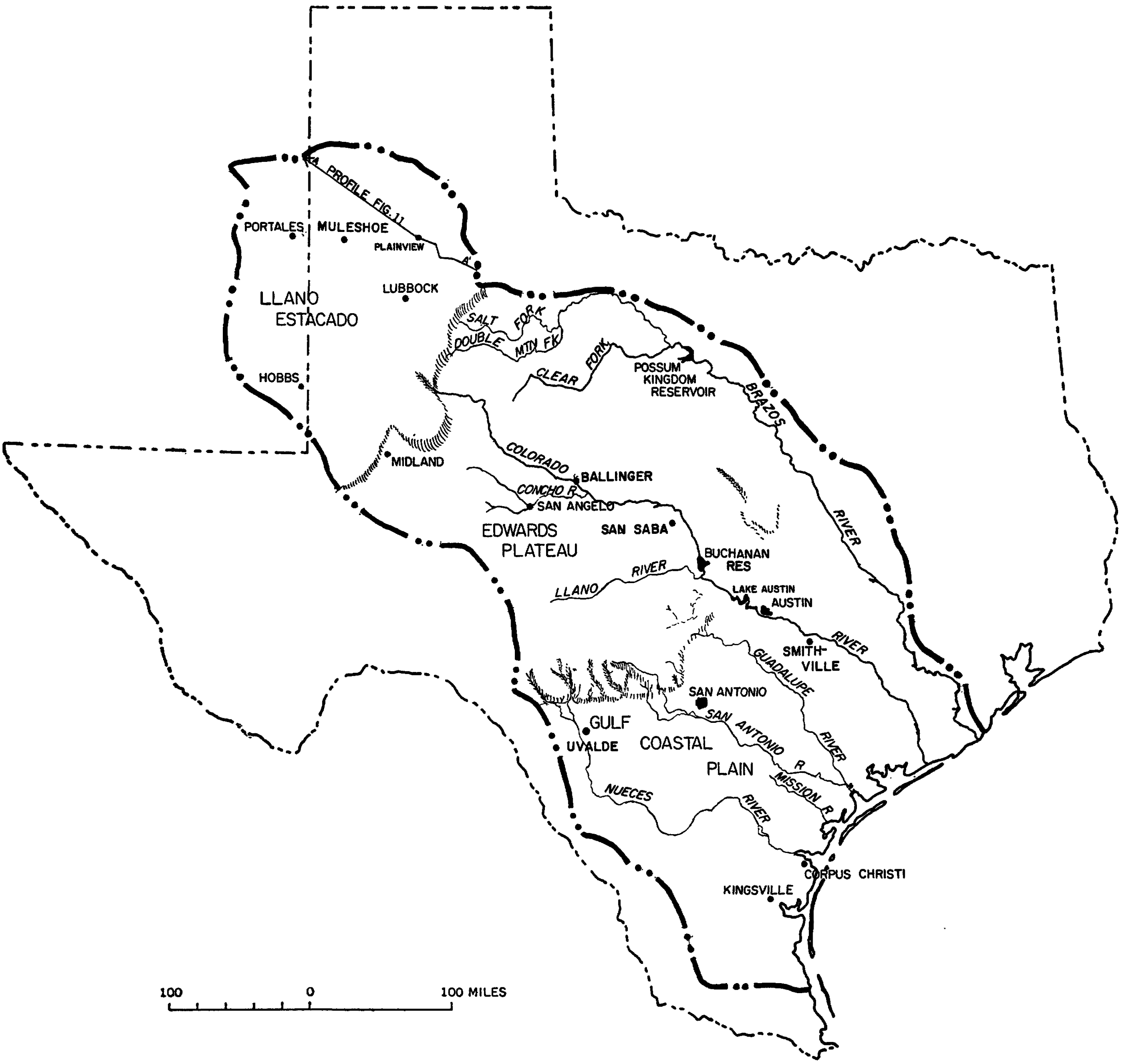

FIGURE 1.—Index map of central and south Texas.

The northern boundary of Texas, except for the Panhandle, is formed by the Red River, which flows to the Mississippi. The State's southern boundary is formed by the Rio Grande. Between these two rivers several other rivers rise within the State, flow southeastward, and empty into the Gulf of Mexico. About 60 percent of the area of Texas is drained by these intrastate streams. The principal intrastate rivers that drain the drought area in central and south Texas are the Brazos, Colorado, Guadalupe, and Nueces Rivers.

The ground-water reservoirs of central and south Texas have still another hydrologic pattern. Several of them are in sandy materials that crop out in bands paralleling the Gulf coast, and each of these is thus crossed by several streams in their courses to the Gulf. A major ground-water reservoir occurs in limestones underlying the Edwards Plateau and the adjacent Balcones fault zone. Numerous tributaries of the Rio Grande, Nueces, Guadalupe, and Colorado Rivers rise in the Edwards Plateau, and depend upon ground water from this huge reservoir for part of their flow. The drainage divides in many places do not coincide with groundwater divides.

The following discussion of central and south Texas is organized by river basins insofar as possible. The Colorado River basin is considered a major unit because of the interdependence of developments up and down the stream, although the river traverses the eastern part of the ground-water reservoir in the Edwards limestone. Farther west, however, the limestone reservoir is considered as a unit, because it influences the flow of several major streams to the south. The streams that drain the Coastal Plain south of the Balcones escarpment—the Guadalupe, Nueces, and others between the drainage basins of the Colorado and the Rio Grande—are then considered as a group because of their community of interests with the limestone reservoir and the ground-water reservoirs underlying the Coastal Plain.

Only the effect of drought upon quantities of water is considered in the discussion of most of the individual river basins. Data concerning the effects of drought upon water quality are meager, and may be summarized for all Texas as follows: Many reports of changes in quality of ground water have been reported during the drought years, but available data do not indicate the causes of the changes. Increasing salinity has been reported in individual wells widely distributed throughout the western half of Texas; in some instances the cause may be related to drought or to increasing withdrawal of water, in others to corrosion of the casing or to other defects in the well, and in still others to surface disposal of brine from oil or gas wells. The changes in quality of many surface-water supplies appear to be related to the drought. According to Burdge Irelan (written communication), of the U.S. Geological Survey office in Austin:

> Drought has undoubtedly resulted in a general increase of dissolved solids, chlorides and sulfates, in water stored in and released from Denison Reservoir on the Red River and Possum Kingdom Reservoir on the Brazos River. Weighted average concentrations of water released from these reservoirs has trended upward from the beginning of sampling (1942 at Possum Kingdom, 1944 at Denison) until this year's [1957] extreme flood. Water sampled in May 1957 was much lower in mineral content at each reservoir than at any time since the first fillings. However, the evidence suggests that evaporation may not have been particularly significant in these changes. Salt springs and seeps located many miles upstream from the two reservoirs apparently contribute a more substantial portion of the salts in the water released from the reservoirs during dry years than during wet years. There is also evidence that a high rainfall on a salt-yielding tributary watershed sometimes results in more than normal loading of the stream waters. In contrast with the Brazos and Red Rivers, the Colorado River reservoir releases do not show increases in chlorides, sulfates, or dissolved solids. This is apparently because the Colorado River has a much smaller portion of its drainage area in the region of Permian outcrops, and also because only a small portion of its flow originates there.

BRAZOS RIVER BASIN

The Brazos River basin is along the margin between the arid West and humid East. On the basis of average annual climate the upper part of the basin above Waco receives less precipitation than the potential evapotranspiration, but there is some surplus of water in the lower part of the basin. The entire basin is marginal also in the sense that the boundary between semiarid and subhumid areas shifts back and forth across it, according to the fluctuations in precipitation from year to year. In wet years the entire basin may qualify as humid, but in the recent dry years the effects of drought have extended over the lower basin and an extensive area farther east. Only the upper part of the Brazos basin is considered here, because this report is limited to the region that is normally arid or semiarid, although it is recognized that the effects of drought have extended farther eastward. In fact, much of the discussion of the upper Brazos basin is applicable also to the lower basin and to other drainage basins farther east in Texas.

The drainage basin credited to the Brazos River above Possum Kingdom Reservoir is about 22,500 square miles, but more than 40 percent of this total is "noncontributing:" that is, it is in the High Plains (p. C22), where the tributaries to the Brazos drain only narrow strips along their channels and the rest of the area contributes no runoff. The contributing area east of the High Plains is in the Permian basin, where sandstone, limestone, and shale beds are interbedded with gypsum and other salines, and where, therefore, much of the ground water is not potable, and a good deal of the surface runoff is of poor quality. The contributing area is also within the North Central Plains soils belt, which is characterized by fairly permeable sandy to clayey loams.

Statistics concerning rainfall and runoff in recent years have been cause for alarm among the residents of the upper Brazos River basin. The average precipitation in the 10 years 1944–53 was about 90 percent of the 1924–53 average, but the runoff at Possum Kingdom Reservoir was only about 50 percent of the 30-year average. The flow of streams characteristically fluctuates more widely than does the precipitation upon their drainage areas. When runoff of the upper Brazos is plotted against rainfall over the basin, it is readily apparent that an annual rainfall of more than 12 inches is required to produce substantial runoff. But comparisons between individual years or selected periods with equivalent rainfall are disquieting: In 1949, for instance, the basin precipitation was slightly greater than in 1935, but the streamflow was only half as great. In the drainage basins of the Salt and Double

Mountain Forks, the average precipitation in the decade 1941–50 was slightly greater than in the decade 1932–41, but the runoff was 17 percent less.

DROUGHT AND CONSERVATION

Several hydrologic studies have been made of the Brazos River basin, some of which include also the adjacent Colorado River basin, in order to analyze and explain the observed reduction in runoff. The reports of these studies are in agreement that the rainfall-runoff relation in recent years has been significantly different from that shown by the records for earlier years; this is clearly shown by double-mass analysis of the records of rainfall and runoff. But the authors of those reports are not in agreement as to the explanation for these changes. Freese (1954) cites a report by Dickson and others (1939) that runoff from individual tracts of land may be reduced 30 to 100 percent during years of normal rainfall by soil-conservation measures, and quotes Stallings (1945) as to the measured effects upon runoff of terracing, contour cultivation, and strip cropping. He then compares rainfall and runoff in the upper Brazos and Colorado River basins for the 10 years ending in 1950 with the rainfall and runoff during 10-year periods of like average rainfall prior to 1943, and finds a decrease in annual runoff approximating 0.3 inch of water over the drainage basins. This he attributes to soil-conservation measures, which began in west Texas in about 1943. Others, after studying the Brazos and Colorado Rivers by subbasins in considerable detail, similarly have concluded that stock ponds and soil-conservation measures have caused a significant reduction in runoff during the period 1942–53.

In a study for the Brazos River Authority, Carothers and Newnam (1956) agree that conservation practices, and particularly stock ponds, are factors in diminution of runoff, but they place them at a lower level of significance. They estimate that, in the drainage basin contributing to Possum Kingdom Reservoir, there are 18,000 stock ponds with average drainage area of 25 acres, surface area of 0.5 acre, and capacity of 3 acre-feet; and they estimate an average water loss of 13,500 acre-feet a year from these ponds. Diversions from the streams are estimated to have reduced runoff to Possum Kingdom by an average of 35,000 acre-feet a year. The total loss by diversions and stock ponds would thus be about 6 percent of the average annual runoff. As to other soil-conservation practices (contour plowing, terracing, strip cropping) Carothers and Newnam recognize that these would reduce the runoff, but consider that the reductions are offset by increased runoff resulting from clearing brush and scrub timber, which consume more water than the grass that replaces them.

Carothers and Newnam attribute most of the change in rainfall-runoff relation since 1942 to a change in rainfall characteristics. Taking first the sample years 1936 and 1944, they note that the rainfall in 1944 was slightly greater, but the runoff was 75 percent less, than that in 1936. The rainfall in 1944 was evenly distributed in relatively small storms, with only two "storm events" producing more than 2 inches of rainfall, and these only slightly more. There were 6 storms of 2 inches or more in 1936, of which one in September was a "gully washer" of more than 5 inches; runoff after this storm reached a peak more than 4 times the maximum in 1944. Comparing then the drought period 1944–53 with the two preceding decades, Carothers and Newnam note a decided reduction in intensity of the rainfall events in the last decade, particularly in storms of 2 inches or more. Their conclusion, that this lower intensity of rainfall has been an important factor in the unseemly reduction in runoff, is in accord with findings in a recent study of the hydrology of the upper Cheyenne River basin of eastern Wyoming (Culler, 1961, p. 86–103).

The correlation of runoff records in the central Texas region (Gatewood and others, 1963) does not offer any clue as to the comparative degree to which the natural rainfall pattern and the artificial effects of soil-conservation practices respectively have influenced runoff. There is good correlation among the records for Brazos River at Seymour, Colorado River at Ballinger, and Middle Concho River near Tankersly, but the drainage basins above all three stations have been the scenes of progressively increasing soil-conservation activities and stock-pond construction.

DROUGHT AND THE "SALT OF THE EARTH"

Possum Kingdom Reservoir, with total capacity of about 725,000 acre-feet, began storing water in March 1941; in the first 4 months of operation it received enough water to fill it three times over, and during 1942 it again received water equivalent to more than twice its capacity. Drought began in 1943, however, and in every one of the years 1943–56 the inflow to the reservoir was less than 750,000 acre-feet, and far below the 1935–42 annual average of 1,200,000 acre-feet. The uppermost graph in plate 1*A* shows the average annual discharge of Brazos River near Palo Pinto, Tex., which is approximately the outflow from Possum Kingdom. A second graph shows that the dissolved load has fluctuated with the runoff, greater in years of high runoff and less in years of low runoff, as is to be expected. Plate 1*B* shows a general increase in the concentration of dissolved mineral matter in the outflowing water during the local 1943–56 drought, although the upward trend was reversed in 1946, 1950, and 1953; the increases were chiefly in sodium, chloride, and sulfate. The abundant inflow during 1957 caused a sharp drop in the concentration of dissolved solids in the reservoir water.

According to the U.S. Public Health Service recommended standards for drinking water (250 ppm chloride, 250 ppm sulfate, 1,000 ppm—permissible, 500 preferable—total dissolved solids), the quality of water in Possum Kingdom Reservoir was marginal when it was first filled in 1941. The increase in salinity during the years of drought was therefore a matter of increasing concern to the Brazos River Authority, which distributes some of the water for municipal and industrial use. The problem became most acute in the years 1954–56, when the quantity of runoff was considerably greater than the average for the preceding 10 years but the quality of the water deteriorated during the 3-year period. Was this a result of increasing ground-water contribution from saline areas, reflecting increased recharge from precipitation? Or had the rains redissolved the soluble salts that had been left in the soils, in ponds or dry channels, during the worst years of drought? Answers to these and similar questions are being sought in current (1958) studies, and may be the basis for action to reduce the salt contribution to Possum Kingdom Reservoir during drought.

One clue to the source of dissolved salts—though not the detailed answer needed for an action program—is suggested by plate 1*C*, which shows the inflow to the reservoir as represented by the record for Brazos River near South Bend, Tex. At this point the river has a contributing drainage area slightly greater than 12,000 square miles, of which about 46 percent is drained by Clear Fork (above Crystal Falls), 16 percent by Salt Fork (above Aspermont), and 12 percent by Double Mountain Fork (above Aspermont). The proportions of total reservoir inflow that come respectively from Salt and Double Mountain Forks, based on gaging records, are shown in the graph. These two tributaries, with 28 percent of the drainage area above the gaging station near South Bend, contributed 25 to 35 percent of the water in the years 1942–45, and also in 1950–51. In most other years of the drought, Salt and Double Mountain Forks contributed a higher proportion of the water: 38 to 47 percent in 1946–49, and 50 to 62 percent in 1954–56.

The upward trend in proportion of water coming from Salt Fork and Double Mountain Fork is significant in the study of quality of the reservoir water, because Salt Fork carries sodium and chloride and Double Mountain Fork carries calcium sulfate in far greater concentrations than are found in Clear Fork. This in turn reflects the differences in geology of the three drainage basins: gypsum and halite both common in Salt Fork basin, gypsum moderately so in Double Mountain Fork basin, and both rare in Clear Fork basin (pl. 1*D*). The fluctuations in mineral content of the reservoir water thus may be in response, at least in part, to geographic variations in precipitation—or drought—throughout the tributary drainage basin. The reservoir water becomes more mineralized when rainfall and runoff are greater in the Salt Fork basin and less in Clear Fork basin, as in 1952 and 1955; and it becomes less mineralized when Clear Fork has the bulk of the rain and the runoff, as in 1950 and 1954.

COLORADO RIVER BASIN

The Colorado River, like the Brazos, has tributaries that rise in the High Plains (although the High Plains contributes practically no runoff), and flows southeastward to the Gulf. According to long-term averages, the annual rainfall at the edge of the High Plains is less than 20 inches, and the rate increases progressively to more than 40 inches at the Gulf. The average (1924–53) runoff accounts for less than an inch of the precipitation in the upper part of the basin—above Ballinger—and for more than 7 inches of the rainfall near the mouth, downstream from Columbus; thus the river originates in semiaridity and traverses bands of progressively increasing humidity. The drainage basin can be subdivided into bands that are distinctive not only as to rainfall and runoff production, but also as to geology and soils, for the geologic "grain" of the region is generally parallel to the Gulf Coast and transverse to the axis of the river basin.

UPPER COLORADO RIVER

The drainage basin of the Colorado River above the gaging station at Ballinger is similar in many respects to the upper Brazos River basin. The similarity applies to rainfall, runoff, geologic formations, soils, and ground-water conditions; and there has been similar controversy in both areas as to the degree of effect of stock ponds and soil-conservation measures upon the runoff since 1942. The drainage area above Ballinger is about 16,800 square miles, but 11,600 of the total is in the High Plains and probably noncontributing.

The lowermost graph of figure 2 shows the annual runoff from the upper Colorado River basin as measured at Ballinger. In the wet years 1941 and 1957 the runoff was about double the 49-year (1908–56) mean of 266,000 acre-feet. In four of the intervening years, 1942, 1947, 1948, and 1954, the annual total reached or slightly exceeded that mean, and in 1945 and 1949 the discharge was equivalent to the median (about 226,000 acre-feet) for the 49-year period. The other 9 years were definitely droughty, for the annual runoff ranged from 10 to 60 percent of the median. Six of these dry years occurred in the period 1950–56, which included the 2 years of least runoff (1952, 1956) in the period of record. For purposes of regional correlations of runoff (Gatewood and others, 1963), the record at Ballinger has been accepted as representing natural streamflow. Thus no corrections have been attempted for the effects of soil conservation measures in recent years, concerning which there is no general agreement even among the experts (p. C4). Even if those measures have modified the runoff significantly, there is the question whether they have caused changes from the natural runoff, or back toward the natural runoff under pristine (pre-white-man) conditions, which have been described (Central Colorado River Authority, written communication) as a "heavy growth of native grasses and vegetation which retarded the runoff of rainfall." In comparison with the records from downstream stations in the basin (fig. 2) the record at Ballinger shows no obvious and effective regulation of the natural runoff.

CONCHO RIVER

The Concho River basin lies between the upper Colorado River basin and the Edwards Plateau, and has some of the geologic and hydrologic characteristics of each, as shown in a report by Willis (1954) which has been the chief basis for the following summary of hydrologic conditions. The upland areas, generally 2,000 to 2,500 feet above sea level, constitute a northward extension of the Edwards Plateau and are underlain by the highly permeable Edwards and associated limestones (p. C11). The broad valleys of the Concho River and its larger tributaries, however, have been cut below the base of these limestones and into the westward-dipping rocks of Permian age, which include gypsum, sandstone, clay, limestone and dolomite. Alluvial terrace and flood-plain deposits in these valleys have a maximum thickness of 125 feet.

Precipitation upon the drainage basin is believed to constitute the source of all potable water within the basin. In most of the area the Edwards and associated limestones constitute the surficial materials and thus the precipitation falls upon permeable materials; however, the limestones do not form an important ground-water reservoir. Although domestic and stock wells obtain supplies of good quality from limestone in several places, most of the limestone is above the water table and therefore unsaturated. Water infiltrating from precipitation moves through the limestone and discharges at springs; this discharge takes place in a short time, judging by the good correlation of the flow of the Middle Concho River near Tankersly with that of the Brazos River at Seymour and the Colorado River at Ballinger (Gatewood and others, 1963). Of these three streams, only the Middle Concho drains any extensive area of outcrop of the Edwards and associated limestones.

Most of the rocks beneath the limestone yield impotable water or no water at all. These rocks crop out in several places along the margins of the valley plains, and some sands and some dolomitic layers yield water of satisfactory quality and quantity for irrigation or for public supplies in the vicinity of their outcrops. However, in some areas of Permian rock outcrops, as for example in the hills just west of the city of San Angelo, there is no ground water suitable for use.

The alluvial sediments underlying the terraces and flood plains of the principal river valleys are the best ground-water reservoirs of the Concho River basin, and they are in the areas most suitable for cultivation of crops. Irrigation by means of wells began as early as 1924 near San Angelo; by 1940, about 800 acres was irrigated from wells, and by 1950 the acreage had increased to 3,700. This irrigation developed as a form of crop insurance in an area that is marginal as far as water supply for crops is concerned. The average annual precipitation at San Angelo is more than 20 inches, of which about 85 percent falls during the growing season; this should be almost enough, provided the rains are well distributed, and in years of greater than average rainfall crops may need no additional supply. But the annual rainfall has ranged from 8 inches in 1917 to nearly 41 inches in 1919, and has been less than the long-time average in all but one of the 14 years 1943–56. Supplemental irrigation is necessary in years of less than average rainfall, and particularly during extended dry periods within a single growing season. The development and use of ground water for irrigation has been of especial value in rainless periods, and has been indirectly a product of drought.

Water levels have declined in wells in all areas where water has been pumped for irrigation, particularly during periods of increasing irrigated acreage and increasing rates of withdrawal. Since these declines have occurred during years of drought, there is a fundamental question whether drought or development has been chiefly responsible. The most rapid declines have been recorded in wells tapping a dolomite in which several irrigation wells have been drilled since 1950 near the town of Veribest; near the center of pumping the static level in some wells was lowered as much as 19 feet in less than a year, and the decline is attributed directly to the pumping.

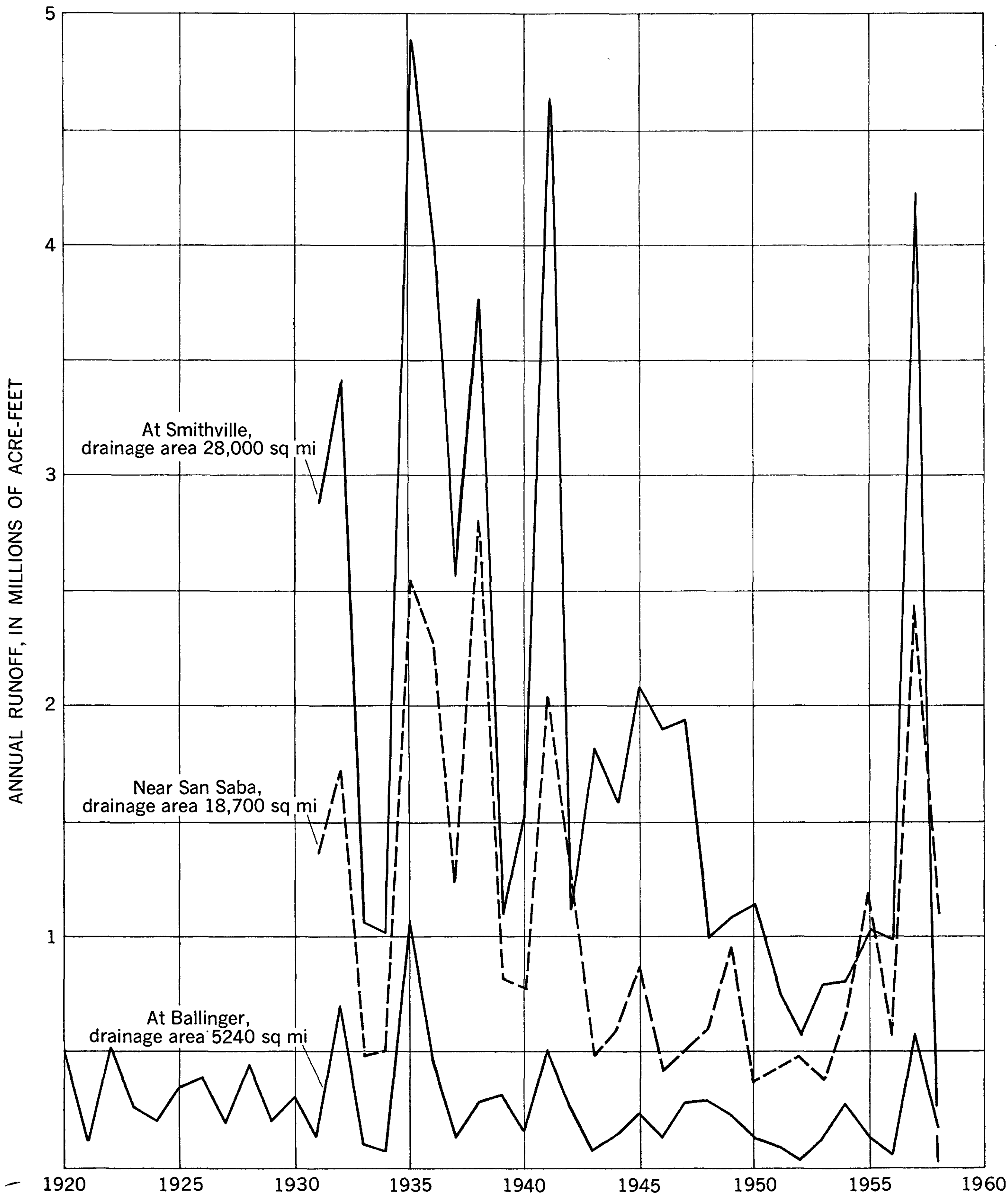

FIGURE 2.—Annual runoff of Colorado River, 1920–58, at three gaging stations.

Most of the irrigation wells obtain water from the alluvium in the river valleys. Water levels have declined in these wells also, particularly during the years 1946–52. The hydrographs of figure 3 include one for an irrigation well (G–128) in the area just northwest of San Angelo, and one for an unused well (G–103) about 8 miles southeast of town. In both these wells the water levels in 1955 were higher than they had been 10 years earlier. From this it appears that the recharge during 1953 and 1954, when precipitation at San Angelo was about average, was sufficient to replenish the storage that had been depleted by pumping during the preceding dry years. The flow of the Concho River downstream from the area of ground-water development was probably less than it would have been under natural conditions, because of this replenishment of ground-water storage. Water levels in wells rose markedly as a result of the abundant precipitation and runoff in 1957.

Lake Nasworthy, which before 1954 was the sole source of municipal water for San Angelo, is at the confluence of the Middle and South Concho Rivers, upstream from the present area of ground-water development for irrigation and therefore not subject to effects from that development. The lake had an initial capacity of 14,000 acre-feet in 1930, but this capacity had been reduced to 12,400 acre-feet by 1953 because of sedimentation. As shown on figure 3, Lake Nasworthy achieved more holdover storage in some drought years (notably 1948–50 and 1953) than in most earlier years, and far more than in 1936, the year of maximum runoff. This apparent anomaly is attributed to changes in the pattern of reservoir operation: in 1936, with severe floods, the primary concern was flood control; in the next decade the lake was maintained at relatively constant level; since 1946, however, the reservoir has evidently stored water whenever available, and although it was practically drained on several occasions during the drought, it has also been filled in most years to higher levels than were reached prior to 1946.

San Angelo Dam, on the North Concho River immediately west of San Angelo, forms a reservoir with total capacity of 396,400 acre-feet, of which 277,000 is for flood control and 38,800 acre-feet is dead storage. The conservation pool, with capacity of 80,400 acre-feet, is used in part as a supplementary supply for municipal and industrial use in San Angelo. The dam was completed in May 1951 and storage began in February 1952, but the "conservation pool" received its first water in mid-April 1954.

The discharge of the Middle Concho River near Tankersly is typical of the highly variable natural flow of streams in this part of Texas: the average annual runoff in 1930–54 was about 30,000 acre-feet, but the channel has had a maximum discharge of 27,500 cfs, and is ordinarily dry during some seasons. The variation in annual flow is likewise great—from 5 times the median to 1/5 the median. During the drought period 1943–56 the annual flow was above the long-term mean in only 3 years, 1948, 1949, and 1954 (fig. 3).

The municipal Lake Nasworthy, the conservation pool in the San Angelo Reservoir, and the alluvium that yields ground water to wells all serve to counteract this irregularity and provide a more stable water supply for use—in other words, to reduce the effects of drought. They do this by storing water when precipitation is sufficiently abundant, and making it available when the natural supply (of rain or of streamflow) is deficient. Declining levels in Lake Nasworthy and San Angelo Reservoir, and also in wells in the alluvium, are inevitable during periods when the withdrawals of water for use exceed the rate of natural inflow to the reservoirs.

MIDDLE COLORADO RIVER

The middle Colorado River basin is taken as the drainage area tributary to the river between the gaging stations at Ballinger and near San Saba. This drainage area of about 7,200 square miles (not including the Concho River basin) is less than one-fourth of the total drainage basin above San Saba, but over a period of about 40 years it has contributed about half the flow measured at the San Saba gaging station (fig. 2). The mean runoff in the middle Colorado section is equivalent to a depth of about an inch of water from the western part of the area and to nearly 2 inches from the eastern part.

Like the Concho River, the San Saba River heads in the Edwards Plateau. The limestone ground-water reservoir in that basin has not been studied, and its effect upon streamflow is not known. Modifications by ground-water storage may well affect the flow of San Saba River at Menard, and thus account in part for the poor correlation of that record with records of nearby streams. However, lacking the requisite data concerning the entire ground-water reservoir in the Edwards and its effect upon streamflow, all that can be said at this time is that the streams originating in the plateau do not all fluctuate in unison, and that the effects of the ground-water reservoir must be variable.

RESERVOIR IN EDWARDS LIMESTONE NEAR AUSTIN

Detailed studies of the ground-water reservoir in the Edwards limestone in the San Antonio area form the basis for rather specific conclusions concerning the hydrology and the effects of drought and ground-water

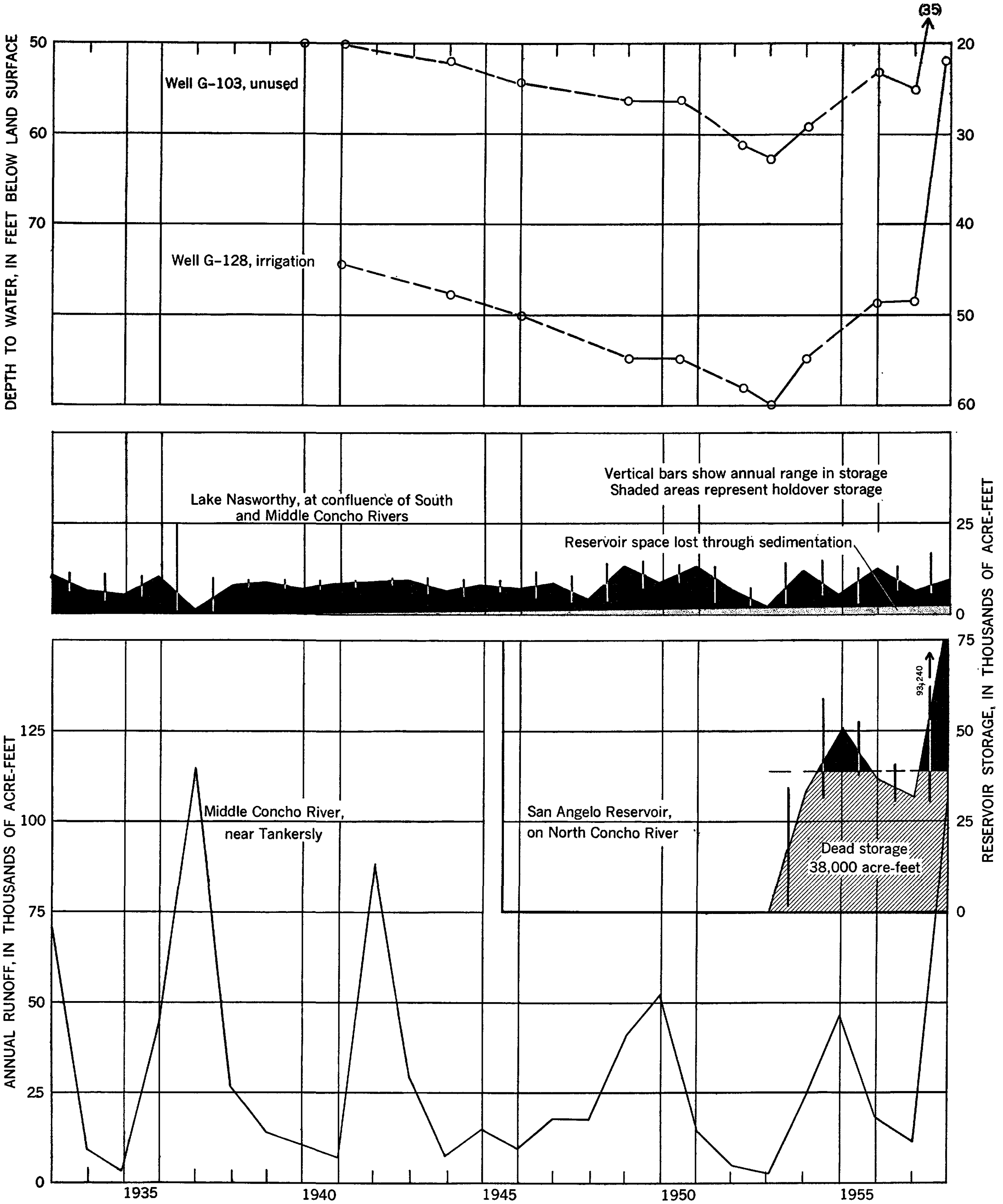

FIGURE 3.—Hydrographs for the San Angelo area, Texas, showing annual fluctuations of water levels in wells, storage in surface reservoirs, and runoff of the Middle Concho River, 1933–57.

development upon the water resources in a broad area west of the Colorado River drainage basin (p. C16). The Edwards and associated limestones occur also within the Colorado River basin in the vicinity of Austin, but there no detailed hydrologic studies have been made.

In contrast to the San Antonio area there has been very little development and use of water from wells in the Austin area. From fragmentary information Petitt and George (1956, p. 61) state that there may be a ground-water divide in eastern Hays County, and that the ground-water reservoir in the Austin area may thus be a hydrologic unit separate from that in the San Antonio region. If this is true, the limestone reservoir in the Austin area is not affected by pumping in the San Antonio area, except perhaps by some shifting in the position of this divide. Thus it appears that the limestone reservoir near Austin has not been affected by development or use of water from wells.

Even so, a variety of factors may affect the storage in and the discharge from the limestone reservoir near Austin. Graphs pertaining to several of these factors are assembled in plate 2. Among these graphs are some that show "inflow" to the area, which is either natural or regulated to only a slight degree; storage or changes of storage in surface and subsurface reservoirs; spring discharge; and stream discharge from the Austin area.

Alternating wet and dry periods of several years' duration are indicated by the graph of annual precipitation at Austin: rainfall was generally less than the long-term mean in the 1930's except in the wet year 1935; the years 1940–46 were relatively wet, and 1941 was the wettest of the 27 years 1931–57; the years 1947–56 were years of drought, and rainfall was generally less than in the preceding drought of the 1930's. The graph of monthly precipitation at Austin gives some indication of rainfall intensities in these alternating wet and dry periods. Monthly rainfall exceeded 7 inches in 15 of the 300 months 1931–55, and 5 of these months were in 1935 and 1936, although the period 1931–39 was generally dry. The wetter period 1940–46 included 7 of these stormiest months, but monthly rainfall exceeded 7 inches only once in the drought of 1947–56.

The runoff of Colorado River near San Saba varies widely from month to month, and in the early years of record the months of greatest runoff frequently coincided with the months of greatest rainfall at Austin. However, the 2 months of greatest runoff (July 1938 and September 1936) were not months of extraordinary rainfall at Austin, and it is evident that flood-producing storms may be restricted to only a part of the drainage basin. Annual runoff near San Saba was greater in 1935 and 1938—2 years within a drought cycle—than in any other year since 1930. From 1939 through 1956 the annual runoff was less than the long-term average in all years except 1941, 1942, and 1955, and the trend was generally downward to all-time lows in 1950 and 1953.

The contributing drainage area above the gaging station on Colorado River at Austin is almost 50 percent greater than that above San Saba, and the average annual runoff is almost twice as great. The runoff as measured at Austin is modified from that measured near San Saba by the storage and regulation afforded by Buchanan Reservoir and Lake Travis, and by the ground-water reservoir in the Edwards limestone. The runoff of Colorado River at Austin has trended generally downward since 1935, more or less like that of the river near San Saba, but there has been less fluctuation in annual discharge, particularly since 1942 when Marshall Ford Dam was completed. Several dissimilarities in the two graphs can be traced to regulation at Lake Travis: the flow at Austin was less than that near San Saba in 1942 and 1949, and almost as low in 1952, because of the increase in storage during those years in Lake Travis; and in 1943 and 1950 the flow at Austin was greater than it would have been under natural conditions, because of releases from Lake Travis. The graphs also suggest some effect of natural regulation by the Edwards ground-water reservoir, particularly in 1944–47 inclusive and in 1953, when the discharge from Barton Springs was fairly high and the river flow at Austin benefited accordingly.

The hydrograph of well L–102 appears to be significant as an indicator of the circulation of water in the Edwards limestone. This well is a dozen miles south of Barton Springs, in the downdropped side of the fault zone. Water levels in this well fluctuate more or less in accordance with the discharge of Barton Springs, indicating that the limestone in the downdropped side of the fault zone is hydraulically connected to the aquifer that feeds Barton Springs. There is also some similarity between these graphs and the graphs for two dug wells where the water level is generally within 20 feet of the land surface and sometimes practically at the surface. One might surmise that this shallow ground water is recharged directly by precipitation, and in that case the similarity in hydrographs leads to the suggestion that rising water levels in the Edwards limestone represent a response to precipitation and recharge upon the outcrop area.

In both shallow wells (H–136 and L–85) the water rose to a maximum in 1938 that was almost duplicated in several subsequent years (1941, 1944–47, 1957). This common level suggests a reservoir so full that any additional increments of recharge are spilled immediately into streams. From 1947 through 1956 the water levels in both shallow wells, and also in the deeper well L-102 that taps the Edwards limestone, were several feet lower than during the period ended in 1946. These lower levels during the drought years are indicators not only of reduced ground-water storage but also of lessened recharge and of lessened base flow in streams draining the area.

LOWER COLORADO RIVER

The Colorado River below San Saba generates hydroelectric power at six dams operated by the Lower Colorado River Authority (LCRA). The principal storage in this system is in Buchanan Reservoir, which has a capacity of 992,000 acre-feet, and Lake Travis, which has a capacity of 1,950,000 acre-feet. The combined capacity of these two reservoirs is slightly greater than the maximum annual runoff of the river recorded at the San Saba gaging station. Thus these reservoirs can provide regulation of the highly variable daily and seasonal flow in the Colorado River above Austin. The considerable variation in the outflow from the lowest reservoir commonly reflects fluctuations in power demand rather than in natural water supply. The graph showing runoff near Smithville, below the LCRA reservoir system (fig. 2), is similar in major aspects to that for the San Saba gaging station, although the runoff at the lower station is about twice as great. Storage began in Buchanan Reservoir in 1937, and in Lake Travis in 1940, and these two reservoirs held back some of the flow in each year from 1937 to 1942, but the total made little difference in the effects of the drought in subsequent years. The chief effect of regulation by these reservoirs has been to make some changes in the yearly pattern of runoff as compared to that near San Saba. Thus the runoff near Smithville in 1943 was considerably higher than in 1942 because of releases of water reservoired in the earlier year. And 1952 was the year of minimum runoff near Smithville because of the great increase in reservoir storage above the gaging station in that year.

These reservoirs are evidently operated as a man of vision would operate the gas tank of his car—keeping the level in the upper half, so that crises are likely to be farther away. Actually this pattern of operation is dictated by LCRA's objective of generating hydroelectric power from the water moving through its reservoir system. There is perhaps no reason why the lower Colorado River should be so completely regulated that its annual discharge would be at uniform rate in wet years and dry, because most of that water flows unused into the Gulf of Mexico. However, the reservoirs are not big enough to be capable of such regulation, even if the need for firm supply were to develop. Thus the natural cyclic fluctuations of wet and dry periods of several years' duration cannot yet be erased by present developmental facilities.

GROUND-WATER RESERVOIR IN THE EDWARDS LIMESTONE

By B. M. Petitt, Jr.

The Edwards Plateau is a conspicuous physiographic and geologic feature in the central part of Texas. Viewed from the south the Edwards Plateau is aptly named, because it is more than 1,500 feet above the coastal plain, having been elevated by faulting along the Balcones escarpment which forms its southern boundary. To the northwest the Edwards Plateau merges with the even higher High Plains (p. C22). Streams that rise in the Edwards Plateau have cut steep valleys and canyons below the upland surface, forming areas of pronounced relief. Much of the plateau has been cut into buttes and narrow ridges, and in many places the limestone that caps the highest hills is all that is left of the original plateau.

The plateau is made up of limestones that are sufficiently vulnerable to weathering and erosion so that the present topography is one of strong relief, but also sufficiently resistant so that the upland has not been eroded away entirely. They have been subjected to percolation and solution by water until they now form one of the major ground-water reservoirs in the Southwest. The limestones include the Edwards limestone, the overlying Georgetown limestone, and the underlying Comanche Peak limestone, which are all of Early Cretaceous age and have a total thickness ranging from about 450 to 1,000 feet. These limestones are here grouped as the Edwards and associated limestones. They are underlain by the relatively impermeable Walnut clay and Glen Rose limestone, and are overlain by the Grayson shale, which is composed largely of clay.

The Edwards and associated limestones form the surface of much of the Edwards Plateau north and northwest of the San Antonio area. Most of the stream valleys along the south edge of the plateau have been cut down to the underlying Glen Rose limestone, and in many places the Edwards and associated limestones have been eroded from the interstream areas. South of the eroded belt, the Edwards and associated limestones reappear in the Balcones fault zone, which forms a curved strip about 20 miles long and 5 to 40 miles wide, and thence dip gulfward under younger formations. Because of this erosion, the ground-water reservoir of the Edwards Plateau is not directly connected with the reservoir system in the fault zone except in a few places. However, the two are hydraulically interconnected because the streamflow from the plateau recharges the reservoir in the fault zone.

The south-draining slope of the Edwards Plateau, with its separation of the limestone reservoir into two parts, provides a unique opportunity to discriminate the effects of natural climatic fluctuations from the effects of man's development and use of water. The streamflow originating in the plateau contains ground water that results from infiltration and deep percolation of rainfall on the plateau, as well as stormflow that feeds directly to the streams with little or no modification by man. This streamflow also provides most of the recharge to the ground-water reservoir in the fault zone, although there is substantial recharge also by direct penetration of rainfall within that zone. The total discharge from the reservoir in the fault zone includes both natural discharge by springs and artificial discharge by wells, which are used chiefly for municipal supply and irrigation in the metropolitan area of San Antonio.

The U.S. Geological Survey and the Texas Board of Water Engineers have collected water-resources data in the San Antonio area for many years, and most of this information has been published in reports of the two agencies, many of which are cited as references. The collection of data has been greatly intensified since 1949, and a progress report of investigations has been published (Petitt and George, 1956).

HYDROLOGY

The extensive net of precipitation stations maintained by the U.S. Weather Bureau in the San Antonio area is supplemented by several stations established by the U.S. Geological Survey. Precipitation is fairly well distributed throughout the year but is heaviest during April, May, and September; the rain falls principally in isolated thundershowers and only occasionally in widespread general rains. The average annual rainfall decreases from east to west. The recent Southwest drought is indicated by less than average rainfall in most of the years 1947–56. The precipitation deficiency has been greatest in the western part of the area, where most of the recharge to the ground-water reservoir normally occurs.

Conditions are favorable on much of the Edwards Plateau for direct infiltration of rainwater. The water after entering the limestones moves laterally through them and issues as springs in the valleys along the south edge of the plateau where streams have cut down to the relatively impermeable Glen Rose limestone. These springs sustain the perennial flow of the streams in the eroded belt between the Edwards Plateau and the Balcones fault zone. As the streams cross the fault zone most of the water again infiltrates into the Edwards and associated limestones. To a lesser extent there is additional recharge to the ground-water reservoir by direct infiltration of precipitation falling on the outcrop of the limestones in the fault zone. Water levels in wells and the discharge of springs rise rapidly after heavy rains, and then recede more slowly. Figure 4 shows the general relation that exists among precipitation, spring flow, and water levels in wells in the Balcones fault zone.

Several gaging stations have been maintained for 20 years or more on streams rising in the Edwards Plateau, and additional stations have been established since 1952 to aid in determination of recharge to the ground-water reservoir in the Balcones fault zone. A large proportion of the runoff occurs within the same month as the precipitation; thus, the runoff from the plateau is rather flashy and not regulated to any high degree by the plateau's ground-water reservoir. Rainfall produces rapid runoff owing to the steep topography in the plateau and widespread exposures of the impermeable Glen Rose limestone in the stream valleys, and also produces an increase in the rate of ground-water discharge through the springs. The mean annual discharge is ordinarily several times as great as the mean discharge during the month of minimum streamflow, except during years such as 1950 and 1951, when storms and floods were inconsequential and the streams carried chiefly water discharged from the plateau's ground-water reservoir.

The effects of the drought of 1947–56, as shown by the graphs in plate 3, include a reduction in the proportion of months of flood discharge, although some high discharges were recorded in 1949, 1952, and 1955; minimum monthly discharges that were as low as or lower than the previous record lows of 1934; and annual runoff in 1956 that was only a small fraction of the average during the decade prior to 1947.

Available data indicate that the ground-water reservoir in the fault zone consists of a highly permeable network of fractures, solution channels, faults, bedding planes, and other openings. Contour maps of the piezometric surface (Petitt and George, 1956, p. 62–63) show that water moves through this network generally from west to east; this has been confirmed by computations showing that two-thirds of the total recharge occurs within the Nueces River drainage basin, but more than 90 percent of the discharge occurs within the Guadalupe River basin. The zones through which water moves are so permeable and so thoroughly interconnected [1] that the reservoir is like a surface reservoir in

[1] The overall permeability of the reservoir does not assure a large yield from a well at any particular place, because the well may miss all the conduits through which water moves, or at least the larger ones.

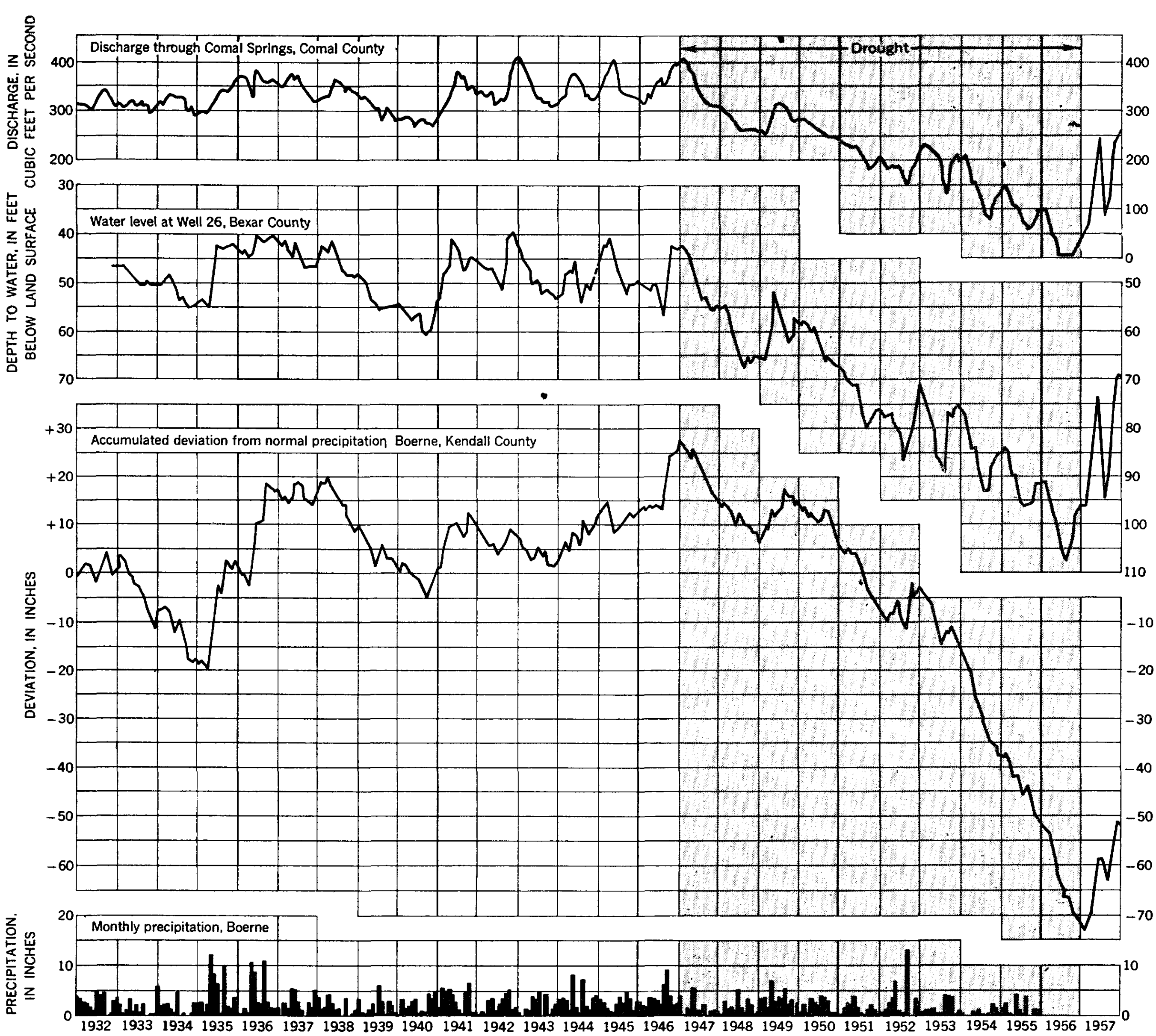

FIGURE 4.—Correlation of discharge from a spring and of water level in a well with precipitation in the San Antonio area, Texas, 1932–57. Drought period shaded.

several respects. Thus any changes in inflow or outflow, though localized, are quickly reflected by changes in head throughout extensive parts of the reservoir. Localized pumping from the reservoir commonly has little effect upon water levels—pumping 17,000 gpm for 17 hours caused a decline of less than a foot in a well 2,000 feet away—but regional pumping of several times that quantity in daylight hours only has caused a diurnal fluctuation of more than 4 feet in wells around San Antonio.

The ground-water reservoir is of course different from surface reservoirs in many respects. For example, water is confined under artesian pressure throughout most of the reservoir. There may be considerable lag between recharge and the changes of water level in wells or of spring discharge that result from that recharge. Thus in May and June 1954 heavy rains caused floods in several tributaries of the Nueces River; most of the floodwater went into the underground reservoir and caused significant rises of water level in wells in Uvalde County. In other parts of the reservoir, however, water levels in wells continued to decline to an all-time low in 1956 or early 1957.

The hydrographs for representative wells throughout the fault zone (pl. 4) show the general uniformity of water-level fluctuations in the fault zone, which is confirmed by records from several dozen observation wells scattered throughout the area and by continuous records from key observation wells. The hydrographs all show a downward trend starting in 1947.

HYDROLOGIC EQUATION FOR THE FAULT ZONE

The hydrologic equation is basically a statement of the law of conservation of matter as applied to the hydrologic cycle. It states that all water entering an area during any period of time must either go into storage within its boundaries, be consumed therein, or be discharged therefrom during the same period. As simplified for the ground-water reservoir of the Balcones fault zone, the equation requires that the difference between total recharge to the reservoir and total discharge therefrom be accounted for by changes in storage. For its solution, therefore, the equation requires adequate data on recharge, discharge, and storage changes.

Recharge estimates have been made for the Edwards limestone in the fault zone by Petitt and George (1956, p. 21–40), who utilized the runoff data of streams originating above the fault zone. Those areas for which there is practically no runoff have been included either as parts of the basins for which estimates of recharge have been made or as separate areas having assumed runoff characteristics similar to other basins. The absence of long-term records on all streams except the Nueces and Guadalupe Rivers made it necessary to extend the records of flow by correlation, in order to complete the estimates for the 20-year period 1934–53. The recharge is distributed throughout the area but occurs chiefly in the western part.

Most of the ground water has been discharged by springs, but the withdrawal of water by wells has been increasing and from 1954 through 1957 it exceeded the discharge by springs. Most of the water is discharged in the Eastern part of the area. The springs are generally along faults that permit water from the limestone to escape into cracks and other channels and flow to the land surface. Wells were drilled beginning in 1885, and Bexar County (San Antonio) alone had about 100 in 1907 and nearly 2,000 in 1953, of which about 250 were of large capacity.

The total recharge to and discharge from the fault-zone reservoir are compared by several different methods in the graphs of figure 5. The differences between annual recharge and discharge (fig. 5*C*) are the quantities that are inferred from the hydrologic equation to have been added to storage, or if below the line of origin, withdrawn from storage each year. In the comparison of accumulated recharge and discharge (fig. 5*B*), the two curves are close enough together from 1934 to 1947 to suggest that the ground-water reservoir was in approximate equilibrium throughout the 14 years; however, from 1947 to 1956 the discharge exceeded the recharge, as shown by the divergence of the curves beginning in 1947. This divergence is reflected in the steep downward trend of the graph of figure 5*D*, showing the accumulated differences between estimated recharge and discharge. These cumulative differences coincide with the decline in water levels in wells since the beginning of drought in 1947.

If the volume of rock that is saturated or unwatered each year throughout the reservoir were adequately measured, the average storage coefficient for the reservoir could be calculated, since the annual water-storage changes have already been estimated from the hydrologic equation. However, only rough estimates of the storage characteristics can be made because of the limitations of the data. Water-level changes in Bexar County well 26 (fig. 4) were used as an index of water-level changes in the reservoir for several reasons: (a) water-level records from this well appear to correlate with records from wells in remote parts of the reservoir; (b) long-term continuous water-level records are available from this well; and (c) insufficient data are available to determine the average change in water levels throughout the reservoir. Figure 6 shows a plot of year-end water-level altitudes versus the estimated difference between annual recharge and discharge. During the period of record the range in water levels in the well exceeded 55 feet. Although the correlation appears to be a straight-line function indicating that the change in storage for each foot of change in water level in the index well through the range observed is about 50,000 acre-feet, the curve should not be extended beyond the limits of the data.

EFFECTS OF WATER DEVELOPMENT AND USE

Under natural conditions the ground-water reservoir of the Balcones fault zone was the source of some of the largest springs in the United States (Meinzer, 1927, p. 29–39). Recreational facilities, irrigated areas, industries, and municipalities have long been established downstream from these springs and have utilized the water, which fluctuated in amount in accordance with the recharge, but had never been known to fail. Wells first tapped this artesian reservoir in 1885. During the 1930's the average withdrawal from wells was of the order of 100 mgd, and this had increased to an estimated 140 mgd by 1946. The estimated average discharge from wells in 1955 was about 240 mgd, of which about 105 mgd was used for municipal supply and about 76 mgd was used for irrigation. The water used for

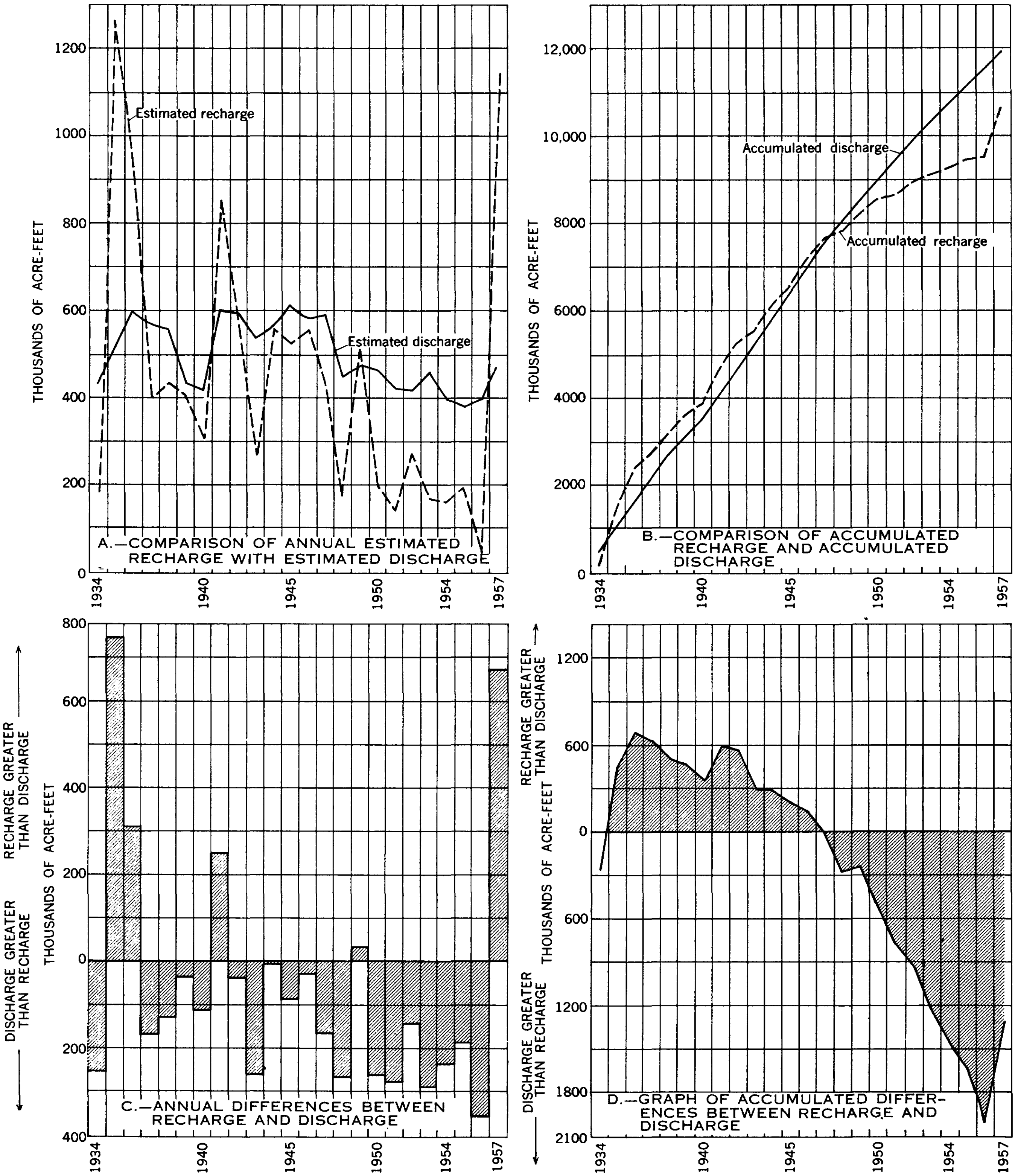

FIGURE 5.—Recharge to and discharge from the Balcones fault-zone aquifer, 1934–57.

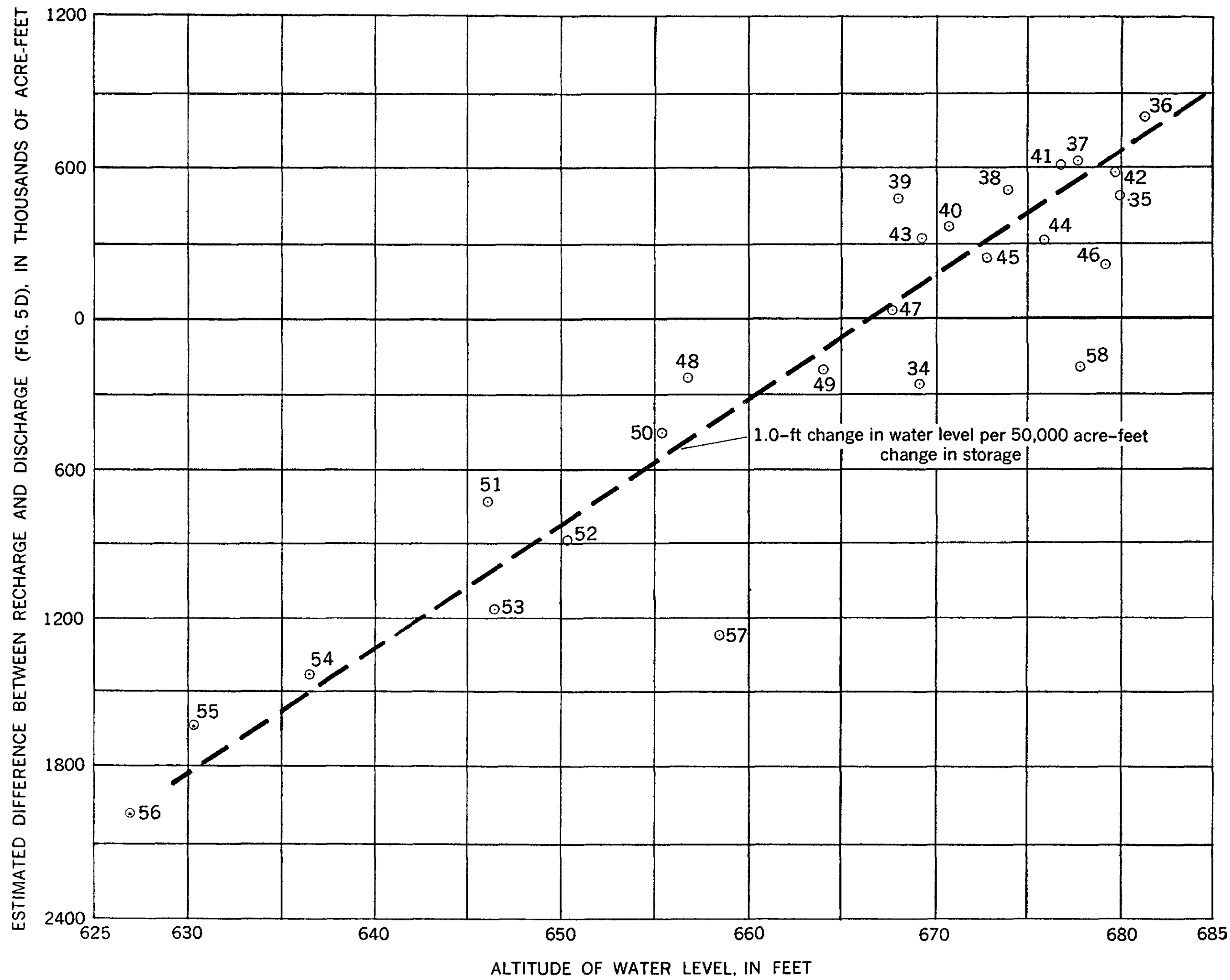

FIGURE 6.—Correlation of year-end water level in well 26, Bexar County, with changes in storage (difference between estimated recharge and discharge).

municipal supply almost doubled in the decade 1946–55, and the increase in use of water for irrigation was even greater. The acreage irrigated in the western part of the San Antonio area increased from 7,000 acres in 1946 to 21,500 acres in 1955.

In 1954 the discharge from wells exceeded the discharge from the springs for the first time. The springs, however, were flowing only a fraction of their average discharge. Figure 7 shows for each year since 1934 the discharge from springs, the discharge from wells, and the total discharge from the reservoir: the spring flow is represented as the shaded portion above the graph showing the discharge by wells, and the top of the graph represents the total discharge from the reservoir. The graph shows clearly that the increased use of water from wells was accompanied by a reduction in the flow of the springs issuing from the fault zone. The flow of Comal Springs is an outstanding example: The maximum discharge is recorded as 425 cfs in 1946, and the mean discharge in the period 1928–55 was about 300 cfs; but the springs ceased flowing in June 1956. The development of wells evidently has not created a new water supply, but represents for the most part merely a change in the point of diversion and use of water that would otherwise issue from springs. The drought of 1948–56 was followed by two relatively wet years, and in 1958 the total discharge from the reservoir was equivalent to that in the wet years 1941–47. Discharge from wells diminished after 1956 and in 1958 springs provided about 60 percent of the total discharge from the reservoir.

EFFECTS OF DROUGHT

The effects of drought are especially evident in the discharge of streams rising in the Edwards Plateau. Springs near the headwaters of these streams have di-

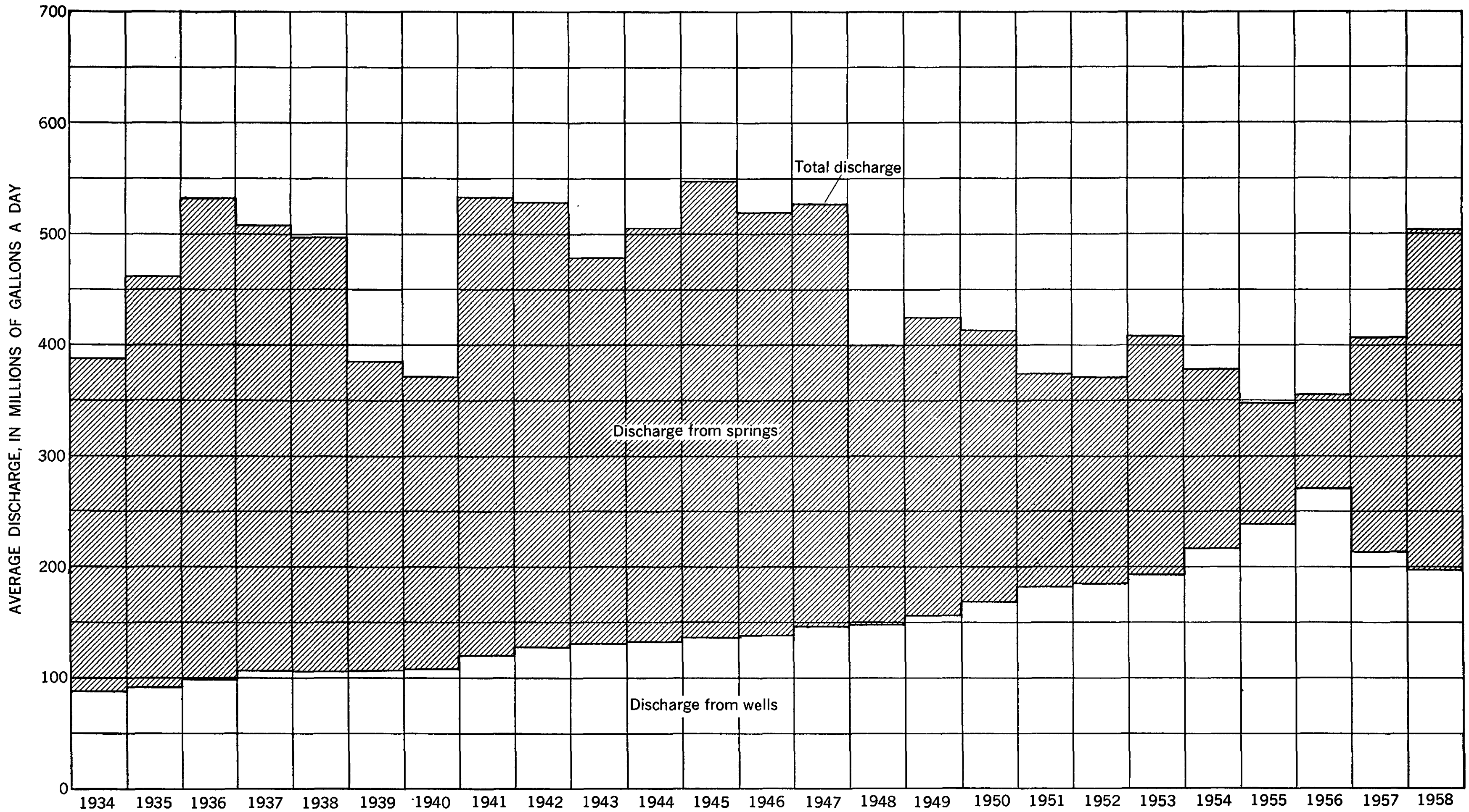

FIGURE 7.—Annual discharge, by wells and springs, of water from the Balcones fault-zone aquifer.

minished to the extent that many streams formerly regarded as perennial have ceased flowing in drought years. The recharge to the fault-zone ground-water reservoir, dependent chiefly upon water from these streams, trended generally downward after 1941 and at an accelerated rate after 1949.

Drought can be held chiefly responsible for the downward trend in total discharge between 1947 and 1956 (see fig. 7) because of the reduced recharge to the reservoir. However, if the drought had been the only factor, and if discharge since 1947 were in approximate equilibrium with recharge as it was prior to 1946 (fig. 5), the total discharge would have been even less. The discharge was greater than it would have been under natural conditions because of withdrawals from wells, which caused a reduction of storage in the ground-water reservoir on the order of 2 million acre-feet between 1947 and 1956.

The decline in discharge of the major springs that flow from the ground-water reservoir in the fault zone is attributed chiefly to the progressively increasing pumping from wells. Indirectly, of course, this increased pumping can be blamed on drought, at least in part, because many new irrigation wells were drilled to enable ranchers to grow forage and cultivated crops in spite of drought.

Although the drilling and pumping of wells has been detrimental to the users of the flow from springs discharging from the fault zone, the ultimate effect of that development may be fuller use of a more stable supply than was available prior to development. The effect of a series of dry years has been observed in the decade 1947–56 with total discharge greater than could have been yielded naturally by the springs. In future series of wet years, it is unlikely that the springs will again achieve the maximum discharges of the past, because of the competing discharge from wells. Thus stability may be achieved by exceeding the natural discharge during dry periods, and then allowing the reservoir to refill in wet periods.

GULF COASTAL PLAIN

The area considered here lies between the Edwards Plateau and the Gulf of Mexico, and between the drainage basins of the Colorado River and the Rio Grande. This area is only a small segment of the entire Gulf Coastal Plain, which forms the coastal border of Texas and extends both southward into Mexico and eastward to Florida. West of the Colorado River this plain is fairly smooth, with a seaward gradient less than 6 feet per mile. It is underlain by a succession of sedimentary layers which have a somewhat greater seaward gradient than the land surface. Most of the formations change considerably in lithology from place to place and especially in the downdip direction. These coastal-plain sediments which crop out in broad bands paralleling the coast are dominant factors in the hydrology of the area.

The coarser sediments of the coastal plain constitute the aquifers that yield water to wells. By comparison with aquifers in the rest of the Southwest, they are relatively fine grained, as suggested by their titles: Carrizo sand, Wilcox sand, Goliad sand, and Beaumont clay (which contains considerable sand), for example. Nevertheless some of them are capable of yielding large quantities of water for irrigation, municipal, and industrial supplies, as shown by the development in the Winter Garden area, and farther east in the Houston metropolitan area.

Permeability of individual sedimentary beds—the characteristic that determines whether the bed will yield much, little, or no water to wells—is also a dominant factor in disposition of rain after it hits the land surface. Some surficial materials are permeable and absorptive and constitute recharge areas for ground-water reservoirs. Others, of which the Blacklands belt through Temple is an example, can absorb little water and thus are likely to be responsible for considerable overland runoff during storms. The streams, of which the Nueces, San Antonio, and Guadalupe Rivers are the largest in the area, cut across the several belts of coastal plain sediments and carry residual or surplus water to the Gulf. If the flow of each stream could be measured at each point where the channel crosses the contact between formations of contrasting permeability, we would doubtless find that the base flow comes chiefly from the permeable bands or aquifers, the storm runoff chiefly from the less absorptive belts.

PRECIPITATION-RUNOFF RELATIONS

Precipitation at Corpus Christi was less than the long-term average of 25.95 inches in each of the 7 years 1950–56, and the average for the 7 years was only 21.1 inches, or 81 percent of the mean. It is to be expected that this deficiency in precipitation would be reflected in the streamflow, directly by reduction in storm runoff, indirectly and perhaps with some lag by reduction of base flow. The larger streams draining the Coastal Plain, however, derive part of their flow from the ground-water reservoir in the Edwards limestone, and that flow has already been shown to be affected both by drought and by increasing ground-water development (p. C16). In order to compare precipitation and runoff in the Coastal Plain alone, the graphs of figure 8 show (a) the monthly and annual precipitation at Corpus Christi, (b) the runoff of Mission River, whose

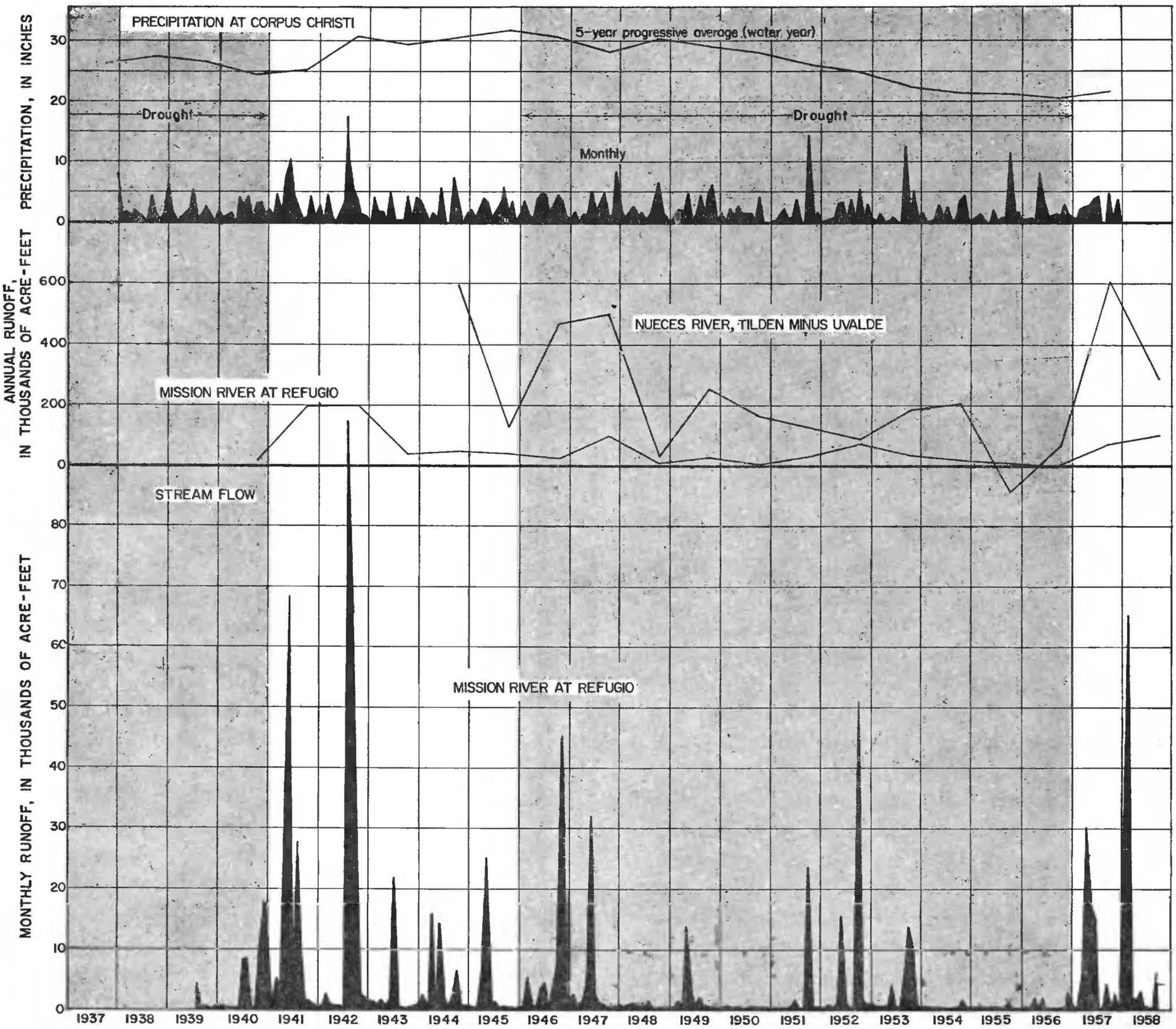

FIGURE 8.—Fluctuations of precipitation and runoff in the Gulf Coastal Plain, Texas, 1937–58. Drought area shaded.

drainage basin is entirely in the Coastal Plain, and (c) the difference between runoff of the Nueces River as measured below Uvalde (at the edge of the limestone ground-water reservoir) and as measured near Tilden (above the confluence with the Frio River).

The pattern of monthly runoff of Mission River is indicative of a drainage basin in which most of the land surface is formed by clay and other impermeable materials. Storm runoff constitutes the bulk of the total runoff in most years, and the years of minimum runoff, 1948, 1950, 1954–56 are years in which there were no rainstorms of high intensity. As shown by comparison with the graph of monthly precipitation, the storm runoff commonly occurs during the same month as the precipitation that caused it; more detailed records might show that the peak runoff occurs within a few hours of the storm. The ground-water contribution is shown best during months of little or no rainfall: In the period of record the base flow was greatest following the months of greatest rainfall in the wet years 1941 and 1942, and was greater than usual following stormy months in 1952. The total runoff was greatest in the wettest years 1941 and 1942, and was also moderately high in 1947 when precipitation at Corpus Christi was 120 percent of the long-term average. However, the annual rainfall and runoff are not necessarily closely correlated, because the storm runoff depends primarily upon rainfall intensity rather than upon annual totals. Thus in water year 1952 the runoff of Mission River was above average, even though the precipitation at

Corpus Christi was only 77 percent of the long-term mean.

A progressive decline in precipitation from 1945 through 1956 is indicated by the graph of 5-year moving averages for Corpus Christi. The precipitation dropped from an annual average of 32.09 inches in the 5 years 1941–45 to 20.54 inches in 1952–56. This trend is reflected to some degree in the graphs showing annual runoff of Mission River and the difference in runoff of Nueces River as measured near Tilden and below Uvalde. The fluctuations in runoff from year to year in both streams are probably caused in large part by fluctuations in flood runoff from intense storms. Such storms may be inferred with considerable uncertainty in the graph of monthly precipitation, and they are hidden completely in the annual totals and running averages that show the general trend in precipitation.

EFFECTS OF GROUND-WATER DEVELOPMENT

As pointed out on p. C18, the Gulf Coastal Plain has several aquifers, some of which are important for water supply near the coast, and others farther inland. Although there are obvious differences in geography and geologic age, these aquifers have several characteristics in common: all are more sandy than the clayey or silty beds that separate them from each other; each aquifer comes to the land surface in a broad belt parallel to the Gulf Coast; each has a gradient toward the Gulf a little steeper than that of the land surface, so that southeastward from its outcrop area it is at progressively greater depth below the land surface; and each aquifer may bear saline water in these deeper zones.

So far as the hydrologic cycle is concerned—that is, the continuing circulation of water as atmospheric vapor, rain, soil water, ground water, surface water, and return to the atmosphere—the most accessible part of each aquifer is in its area of outcrop. This is the recharge area, the area where water is added to the aquifer by infiltration of precipitation. Doubtless part of the water added to the aquifer is also discharged within this area of outcrop, but chiefly near the boundary where the aquifer is covered by clay or other comparatively impermeable materials, and particularly at stream channels which cut into the aquifer. Under natural conditions the buried part of the aquifer, by far the largest proportion in total volume, is filled with water at all times, and that water is under sufficient pressure to raise it to the land surface, or higher in some places. There is doubtless some natural discharge of water from the buried part of the aquifer—to stream channels, to the land surface, or possibly to the Gulf—but such discharge requires movement of water through the overlying clay beds. The artesian pressure is an indication not only of the possibility of such upward movement, but also of the resistance to such movement through the overlying and confining strata. We do not have, for any specific aquifer of the Coastal Plain, data as to the quantity of recharge in a specified period, or the proportions of that quantity that are discharged from the unconfined and the confined parts of the aquifer. It may well be that, for at least some confined sands, the term "aquifer" (water-carrier) is a misnomer, and "cul-de-sac" would be more descriptive of the enormous facilities for water storage, the very respectable entryway from the recharge area, and the comparatively negligible opportunities for flowthrough.

Some generalizations can also be made for all aquifers with respect to prospects for ground-water development, neglecting the differences in permeability from place to place within each aquifer. First, the prospects for replenishment of the water withdrawn through wells would be best in the area of outcrop, or the recharge area, of each aquifer. But the expected yields would be smallest along the upper (northwestern) edge of this area, because the saturated thickness there is least, and would increase toward the southeast. At the contact between the outcrops of the aquifer and the overlying finer materials, wells could tap the full thickness of the aquifer, all of which would be saturated under virgin conditions, and those wells would benefit by replenishment from local precipitation as well as from precipitation upgradient in the recharge area.

Wells drilled southeast of this recharge area, where the aquifer is buried beneath confining layers, might have an initial yield greater than wells in the recharge area, and might be more desirable because of capability of flow by artesian pressure. But for sustained yield the distance from the recharge area is an important factor, because the water taken from wells can be replenished only from that area.

These generalities are an essential preliminary to a discussion of the effects of wells upon ground-water storage, and upon ground-water discharge to streams. Some wells may be located in parts of the recharge area where the water table was originally quite shallow, and the wells by pumping have created space for recharge by water that would otherwise have run off overland to streams; no example of such conditions can be cited, however. Some wells are known to be in the unconfined part of aquifers where by pumping they take some water that would otherwise have contributed to the base flow of streams; such wells have obviously been a factor in the observed reduction of streamflow in recent years. Still other wells have tapped the confined parts of aquifers at places where all the water they have withdrawn has as yet had no effect upon the flow of water within or from the recharge area.

In most of the localities of intensive ground-water development in the Coastal Plain—as for example in the Winter Garden area in Dimmit, Zavala, and Atascosa Counties (White and Meinzer, 1931; Sundstrom and Follett, 1950; Outlaw and others, 1952)—wells are distributed over extensive areas, including both the confined and unconfined parts of the producing aquifer. Some of these wells may depend entirely on water in storage, others may tap replenishable supplies and therefore may be affecting the natural discharge of ground water to streams. Discrimination of these various effects is difficult in the composite picture. It is far easier to explain the factors involved in the history recorded in areas of relatively small and isolated development.

Kingsville, in Kleberg County, provides a good example of the effects of pumping upon water levels in wells; the drought had no clear-cut effect except possibly as it made someone thirsty enough to use more water than usual. Most of the pumping is by Kingsville's four municipal wells, which increased their average draft from 0.8 mgd in 1941 to 3.5 mgd in 1954. The Missouri Pacific Railway pumps about 0.3 mgd from a well in Kingsville, and the Naval Air Station in 1943 began pumping about the same amount from a well 5 miles southeast of town. All these wells obtain water from the Goliad sand, and there is no other pumping from that aquifer for 6 miles in any direction, except for the small amounts taken from numerous rural domestic and stock wells. The Goliad sand, as much as 150 feet thick, is 600 to 700 feet below the land surface at Kingsville, but crops out in a north-trending belt 25 to 40 miles west of the town. The pumpage at Kingsville and its effects upon water levels in wells are shown diagrammatically in figure 9, covering the period 1932–58.

Flowing wells in the vicinity of Kingsville were used for irrigation as early as 1904; some wells had ceased to flow by 1908, and by 1910 pumping was started. The irrigation development was at a maximum in 1912, when about 3,500 acres was irrigated from wells. Pumping for irrigation became unprofitable by 1914, and since that year the principal draft on the reservoir has been for municipal and railroad supply at Kingsville. This draft had created a sizable cone of depression in the piezometric surface even by 1932; the cone has deepened progressively, as shown in profiles for several subsequent years (fig. 9*C*), and by 1956 had a shape as shown by the contours of equal lowering of artesian head (fig. 9*A*). The hydrographs (fig. 9*D*) indicate little change in water levels in any well along the profile between 1932 and 1941, and little change even in subsequent years in the wells farthest from Kingsville. However, the pumping has caused downward trends of water levels since 1941, at decreasing rates with increasing distance from the center of pumping.

The westernmost well (at left edge of the profile) is within a quarter of a mile of the edge of the unconfined part of the Goliad sand, and thus is near the edge of the recharge area. The water level in this well has changed very little in the 20 years, indicating that either (a) the cone created by pumping has not yet extended to the recharge area, or (b) the recharge area constitutes a "line source" for the confined aquifer and feeds water into the edge of the confined zone as rapidly as it can be drawn from there toward the center of pumping.

EFFECTS OF DROUGHT

The effects of drought upon the developed sources of water supply in the Gulf Coastal Plain range from negligible to highly significant. Minimum effects are believed to be typified by the Kingsville artesian well field. It is true that water levels in wells near Kingsville have declined more rapidly since 1943 than in earlier years, as shown both in profiles and hydrographs of figure 9, but this is undoubtedly due at least in large part to the increasing rate of pumping. Obviously the increase in pumping may have resulted partly from drought, and to that extent the declining water levels may be attributed indirectly to drought, but it cannot be said that water levels have declined because of reduced recharge, because there has been negligible decline in the well nearest the recharge area. In other areas of ground-water development, a determination of the effects of drought would require analysis of any observed changes in storage in relation to pumping draft, natural ground-water discharge to streams, and recharge to the ground-water reservoir. It is likely that in many areas the effects of drought cannot be reliably estimated until after the drought is ended—in other words, until we have observed the effects of a few wet years for comparison.

As shown in figure 8, the runoff from the Coastal Plain fluctuates more widely than the precipitation, and thus during drought years is a far smaller percentage of the long-term average than is the precipitation during the same year. This is characteristic of streamflow (Gatewood and others, 1963): under natural conditions, the total evapotranspiration of water from year to year is a fairly constant quantity, and when subtracted from the widely varying gross supply from precipitation, leaves a residual that varies even more widely. The development of water supplies by man is likely to re-

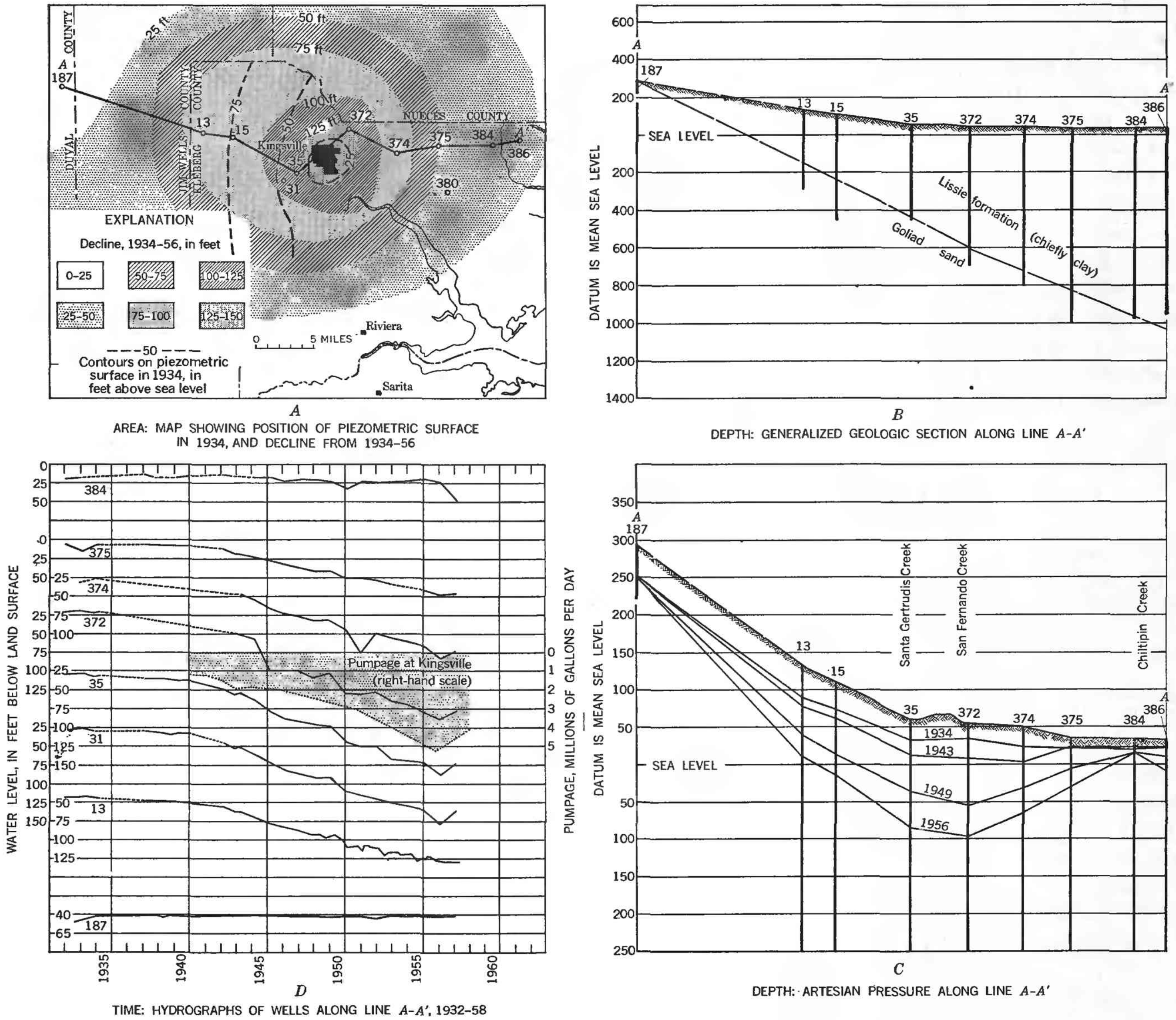

FIGURE 9.—Four dimensions of ground-water development at Kingsville, Texas: area, depth, and time. Wells are numbered on all charts as on WSP 773, p. 221–226, and WSP 776.

duce that residual; but once the development has stabilized, the quantity used by means of wells, canals, stock ponds, and other facilities, is likely to be fairly constant from year to year, so that there is a further accentuation in the variation in runoff between wet and dry years.

The wide fluctuations in runoff of these Gulf Coastal streams, and the very low flows in dry years, may be contrasted with the flow of the Colorado River, which is sufficiently regulated by the LCRA reservoirs that the annual discharge from the lowest reservoir is more uniform than the streamflow in the middle Colorado River basin (p. C10); or with the outflow from the upper Rio Grande basin at Fort Quitman (Thomas and others, 1963), which is fairly uniform and also very small because of regulation and use upstream.

LLANO ESTACADO, TEXAS AND NEW MEXICO[1]

Although precipitation was significantly below the long-term average in the years 1952–56, the Llano Estacado qualifies only as a marginal area of Southwest drought on the basis of the criteria set forth by Thomas (1962). In a report that is intended primarily to consider the effects of drought, the Llano Estacado might well be omitted, or at most be considered only briefly. However, in a decade when the entire Southwest was

[1] Adopted largely from Guam (1953).

feeling drought, the Llano Estacado also experienced several years of deficient rainfall, during which there were many effects upon water resources that might be attributed to drought. Thus, the water situation in the Llano Estacado is worth summarizing here.

The Llano Estacado is the part of the High Plains that lies south of the Canadian River in Texas and New Mexico. Its area is more than 30,000 square miles, and it is bordered by conspicuous escarpments on the east and the west. During the first half of the 20th century, the population of the Llano Estacado increased nearly thirtyfold. This phenomenal increase resulted largely from the development of oil and gas, ranching and dry farming throughout the area, large-scale irrigation by water from wells, and growth of trade centers such as Amarillo, Lubbock, and numerous other cities and towns. The growth in population has been accompanied by an even greater increase in economic wealth. The story of the economic growth is one of an abundance of oil, gas, fertile land, and ground water. In 1918 the Panhandle gas field was discovered, in 1927 oil in large quantities was discovered, and from 1914 to 1956 the area of irrigation grew from 16,000 to more than 4 million acres.

Hydrologically the Llano Estacado is almost completely isolated from the regions adjacent to it. It is more than 1,000 feet higher than adjacent streams, and thus can receive no water from them. Streams have cut channels back from the bordering escarpments and from the canyon of the Canadian River, but most of the plain is level or slightly rolling, and is pockmarked by thousands of depressions, as much as a mile across and 50 feet deep. Most of the Llano Estacado drains into these depressions; ponds form after intense rainstorms, and some may remain for years. Thus, although the Llano Estacado is commonly subdivided into portions that are credited to the drainage basins respectively of the Pecos, Canadian, Red, Brazos, or Colorado Rivers, most of the areas so credited are recognized as "noncontributing," and the total runoff from the Llano is a negligible proportion of the total precipitation.

CLIMATE AS A CONTROLLING FACTOR

As pointed out by (Thomas 1962), the Rocky Mountains form a topographic barrier which induces a large amount of precipitation of water vapor that originates either in the Pacific Ocean or the Gulf of Mexico. The lower land immediately east of the Rockies, but west of the High Plains, lies in the rain shadow of this barrier to Pacific moisture, and has a semiarid climate because of it. The broad Mississippi Valley east of the High Plains is not dependent upon moisture from Pacific sources, but receives rain originating chiefly in the Gulf of Mexico. The High Plains also receive most of their moisture from Gulf sources, but are west of the zone of abundant rainfall. Thus they lie in a semiarid belt, bounded on the west by a belt of greater aridity and on the east by a more humid region. This general climatic pattern has probably persisted since the development of the Rocky Mountain barrier, and thus for a relatively long period in geologic history.

CONTROL IN GEOLOGIC HISTORY

Although rivers are now relatively unimportant in the hydrology of the Llano Estacado, they have been of major importance in the geologic history of all the High Plains: they were instrumental in the development of a vast debris plain between the Rocky Mountains and the Mississippi Valley, and subsequently in the erosion of that plain, leaving small remnants of which the Llano Estacado is the southernmost. As pointed out by Lohman (1953, p. 70)

> If we could turn back the geologic clock sufficiently we would find a series of streams flowing eastward from the ancestral Rockies in a succession of broad valleys and low intervening divides. Ultimately a somewhat undulating plain was eroded on the sedimentary rocks of the region. Then renewed uplift of the mountains greatly increased the erosive power of the streams and supplied the streams with enormous quantities of rock debris. The region being relatively arid then as now, the streams were capable of transporting only a small part of the debris as far as the sea—most of it was dropped along the way, from the foot of the mountains eastward. Thus overloaded, the streams gradually filled their valleys and eventually buried the intervening low divides. With gravel, sand, and silt the streams continually built their flood plains higher than adjoining areas. Seeking lower levels at every opportunity, the streams shifted back and forth many times, always filling the lowest areas. Ultimately a remarkably smooth and gently inclined debris plain spread eastward from the Rockies.
>
> The High Plains as we find them today are a remnant, perhaps less than a third of the original debris plain * * *. Between the bold western escarpment and the mountains, and east of the more subdued eastern escarpment, the sediments of the original debris plain have been stripped away by erosion, again exposing the platform of older rocks upon which the plain was built.

In this erosion of the vast debris plain, as in its original development, the climatic belts of aridity, semiaridity, and humidity appear to have been controlling factors. The present High Plains occupy the semiarid belt, where the precipitation was sufficient to develop a protective sod. According to Johnson (1901, p. 629)

> The tufted growths of bunch grass and light "brush" of the arid zone fail almost completely in protection because they do not constitute a continuous cover; and sod, on the other hand, is completely effective, not because it resists the erosive work of well-developed drainage, for that it cannot do, but because it prevents the initiation of drainage. It is effective against

the first faint beginnings. The great plateau surfaces of the High Plains have to show no systems of drainage, because, presumably, from the commencement of the present erosion stage they have been sod covered, as at present [1900]. In other words, the High Plains have endured as alluvial plateaus since Tertiary time, or at least since the opening of the Pleistocene.

Thus the High Plains may be regarded as comprising a fossil land surface.

CONTROL IN PRESENT ECONOMY

The Llano Estacado is within the Great Plains meteorologic region as discussed and outlined by Thomas (1962). The 64-year record of precipitation at Amarillo has been taken as representative of this broad region. The record for Plainview is also more than 60 years long, and at several other communities on the Llano Estacado the records of precipitation extend back for more than 40 years. These records show that the average precipitation on the Llano Estacado is about 21 inches, with a geographic range from 16 inches at Lovington, N. Mex., to 22 inches at Tulia, Tex. The wettest year was 1941 with an average precipitation of 38.4 inches and the driest year 1917 with an average of only 10.5 inches. About 75 percent of the year's precipitation falls during the principal growing season, April–September. About 37 percent of the precipitation falls in showers of less than half an inch a day, and these showers contribute little or nothing to the recoverable water supply; only about 10 percent falls in storms that exceed 2 inches in 24 hours.

Rough computations indicate that in an average year the precipitation on the Llano Estacado totals some 35 million acre-feet of water. Of this only a very small part, perhaps about 1 percent, flows out from the area in streams or underground (Theis, 1937). Thus, nearly all the water that falls as precipitation is returned to the atmosphere within the area. The climate of the region is dry enough, and in summer warm enough, to encourage return of water to the atmosphere at a rate far greater than the average precipitation. Judging by records from 5 evaporation pans, the yearly evaporation from a free water surface is about 70 inches, or nearly 3½ times the average yearly precipitation. The growing-season (April–October) evaporation of 50 inches is similarly about 3½ times the average concurrent precipitation. Thus, if the precipitation were evenly distributed in light to moderate rains, practically all of it would be returned to the atmosphere from the soil upon which it falls, either by evaporation or by transpiration of grasses and other vegetation. Under such a water economy, contributions to the resources of surface water and ground water would be nil. For all practical purposes, this is the situation on the Llano Estacado in most years.

INADEQUACY OF PRECIPITATION

From paleontologic and other geologic studies there is convincing evidence that the Llano Estacado has been grassland for millions of years, and by inference that the precipitation has been adequate for that native vegetative cover. However, the average precipitation is less than the potential evapotranspiration (Thomas, 1962) and the region is therefore classed as one of water deficiency. Thus, even if rainfall were well distributed each year in accordance with long-term averages, it would not be adequate for man, unless he perpetuated an economy on the basis of the native grass cover; or unless, by such drastic measures as paving, he collected the precipitation on large areas for use on small areas. Crops that thrive in humid regions could not survive under the average climatic conditions of the Llano Estacado.

The climate of the Llano Estacado, however, is usually far from average. Wide and frequent variations from the average conditions are characteristic. Annual precipitation has ranged from one-half to almost twice the long-term average, and there are also wet and dry periods of several years' duration. Thus in the years 1919–28 the average annual precipitation at Amarillo was 24.4 inches, but in 1929–40 it was only 17.39 inches. For dependence upon soil water derived directly from precipitation, the distribution and amounts of rainfall in individual storms in the growing season are of critical importance, and here the variation is extreme. As shown by figure 10, less than half the total annual precipitation at Muleshoe, Tex., occurs in storms exceeding 0.5 inch of rain in a 24-hour period; storms of 1½ inches in 24 hours can be expected about once a year, and storms yielding 3 inches in 24 hours may occur every 6 or 7 years.

SUPPLEMENTARY SOURCES OF WATER

A considerable variety of water sources may be utilized to supplement the precipitation as necessary for crop requirements, but those sources can be perennial only to the extent that they can be replenished periodically by precipitation. Inasmuch as more than 99 percent of the water from precipitation is returned to the atmosphere by evapotranspiration within the Llano Estacado, the greatest opportunities—speaking volumetrically—appear to lie in a more beneficial use of that water during its sojourn in the soils and ponds of the Llano.

Contour farming, terracing, and summer fallowing have been recognized as effective methods for soil-water conservation. By contouring and terracing, water is held on the soil in the area where it falls, thus reducing the local runoff during intense rainstorms. By summer

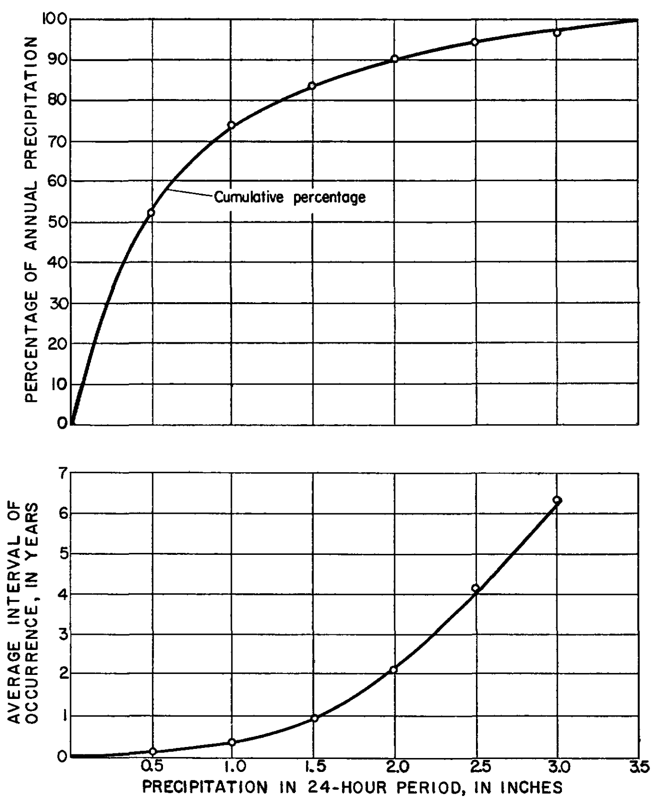

Figure 10.—Frequency of precipitation at Muleshoe, Tex., 1922–52: percentage of annual precipitation and average recurrence interval of daily precipitation in range 0 to 3.5 inches.

fallowing, the crops planted in alternate years have the benefit of two seasons of infiltration, thus reducing the hazard of inadequate water supplies.

The water accumulating in depression ponds has been estimated to be more than a million acre-feet a year on the average. Some enterprising farmers have made a direct attack on this supply by pumping from ponds, but they work under two major handicaps: First, the ponds are inevitably on the lowest parts of their farms, so that the water must be lifted to all points of irrigation; second, the pond supplies are most abundant in wet years when they are needed least for irrigation, and they dwindle or disappear in dry years.

The water that leaves the Llano Estacado either as streamflow or as natural ground-water discharge (of the order of 100,000 acre-feet annually) is more readily available for use of people below the escarpment than to those occupying the High Plain. Springs that are sufficiently large and accessible have long been utilized along the margins of the plain.

The flow of streams is considerable at times, but so infrequent that it is difficult to justify large expenditures for regulating structures, either for flood control or for water supply. Gaging stations have been maintained since 1938–39 on three streams. The total flow of the Prairie Dog Town Fork of the Red River near Canyon amounted to only 83,000 acre-feet during the 8-year period 1940–47, and of this amount 66,000 acre-feet or 80 percent ran off during the wet year 1941; runoff in the other years averaged only 2,400 acre-feet. On the Double Mountain Fork of the Brazos River at Lubbock, the 8-year runoff was only 9,000 acre-feet, of which nearly 7,000 acre-feet occurred in 1941. The 8-year runoff of White River (Running Water Draw) at Plainview amounted to 35,000 acre-feet, of which 31,000 acre-feet occurred in 1941.

The chief source of water to meet the requirements of crops—and the only source of water for municipal, industrial, and domestic supply—is the ground-water reservoir that underlies the entire Llano Estacado. The quantity currently pumped from this reservoir is far greater than can conceivably be replenished by precipitation, and the water therefore is coming chiefly from storage.

DEVELOPMENT OF GROUND WATER

THE GROUND-WATER RESERVOIR

In the Llano Estacado—as in most other parts of the High Plains—the story of ground water is linked closely with the history of the building and subsequent dissection of a vast piedmont alluvial apron east of the Rockies. The Ogallala formation, comprising the materials of which this alluvial plain was built, is the dominating ground-water reservoir of the region. The boundaries of this formation are essentially the boundaries of the reservoir, and indeed of the Llano Estacado (fig. 11). At some places the Ogallala formation is thin or absent, and there the older rocks become of importance to prospective ground-water users. Under most of the Llano Estacado the rocks immediately under the Ogallala are far less permeable or they contain highly mineralized water, so that generally they are not sources of usable water. In some areas in the southwestern part of the plain, however, the Ogallala is underlain by limestone and sand which are capable of yielding moderate quantities of water to wells, locally as much as 1,000 gpm.

The Ogallala formation is composed of silt and clay, sand, gravel, and caliche; commonly there is a wide variation in materials within short distances, both laterally and vertically. Generally, though not universally as penetrated in wells, the material is of coarser texture in the lower part of the formation, predominantly silt and clay in the upper part. From this it may be deduced that in the first stages of the alluvial-plain building the streams had greater carrying power but subsequently, as mountains were worn down and the plains built up, they deposited finer material. Lateral

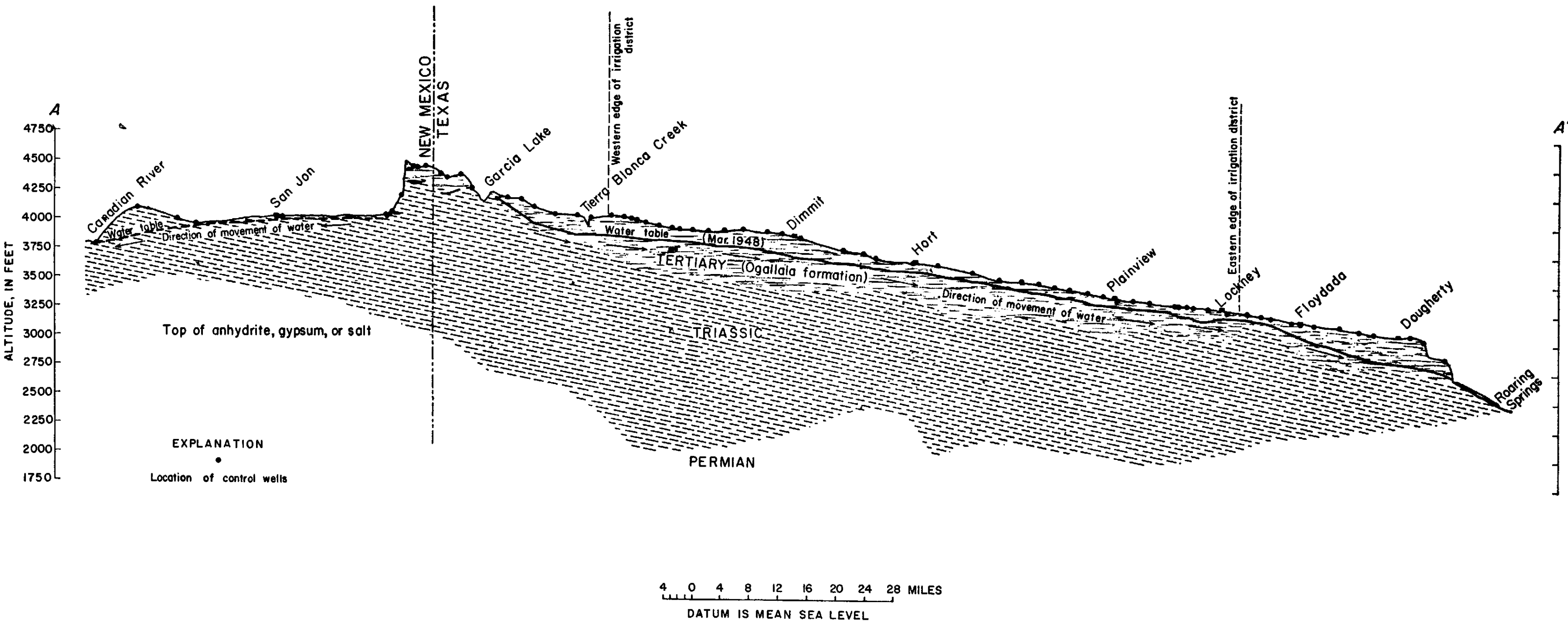

Figure 11.—Section southeastward across Llano Estacado, N. Mex. and Tex., along line *A–A'* of figure 1.

variation in materials is believed to be related to distance from main channels of the depositing streams. For example, the thickest and most productive water-bearing sands are found in a wide strip roughly parallel to the present White River; outside this strip there are buried ridges and hills of older rocks.

Over the Llano Estacado the Ogallala formation ranges in thickness from 0 to 600 feet or more. It has been estimated that the total water stored in the reservoir prior to the drilling of wells was of the order of 400 million acre-feet.

HISTORY OF DEVELOPMENT AND USE

Probably the first domestic wells to tap the water-bearing sands of the Llano Estacado were drilled before 1890. Irrigation from wells was begun at Plainview in 1911, and by 1914 about 140 wells had been completed in the Llano Estacado. Development was slow for the next two decades, and by 1934 only 35,000 acres was being irrigated from 300 wells. From 1935 to 1940 there was a steady increase in number of irrigation wells, irrigated acreage, and quantity of water pumped, and since 1943 the expansion of irrigation has been spectacular, as suggested by figure 12. During 1956 about 35,000 wells pumped 5½ million acre-feet for irrigation of 4 million acres, chiefly of cotton. At first the wells were concentrated in numerous separate areas, but as the irrigated acreage has increased the wells have necessarily been distributed over broader and broader areas. As of 1957 the Llano Estacado had an average of more than 1 irrigation well per square mile, and in some areas there were as many as 12 per square mile.

EFFECTS OF DEVELOPMENT AND USE

The most conspicuous effect of pumping on the Llano Estacado has been a progressive lowering of water levels in wells. It is evident that the great bulk of water pumped has been taken from storage. As shown by the hydrographs of figure 13: In a well in Floyd County, Tex., the water level has declined progressively since 1943, the total exceeding 75 feet by 1958; in the wells in Lamb and Crosby Counties water levels have declined since 1947, and at accelerated pace since 1951; the water levels in the wells in Lea County, N. Mex., began to decline in 1951 or later. These declines are related to the development of irrigation wells and to the rate of pumping and the positions of the irrigation wells with respect to the observation well. Assuming that all the water pumped is taken from storage, and that the total water in storage before pumping began was 400,000,000 acre-feet, it is estimated that pumping by 1956 had reduced the quantity in the reservoir by more than 25 million acre-feet. With pumpage at an annual rate of nearly 6 million acre-feet, the amount still in storage is enough theoretically for about 60 years of pumping.

However, this pumping is not distributed uniformly over the area but is concentrated in certain districts, and even pinpointed in parts of those districts. As a result, water levels have declined 50 feet and more in areas of a few square miles, for example southeast of Plainview, southwest of Amarillo, and near Lubbock, Tex. On the other hand, the level of the water table has changed very little over extensive areas where little or no water is being pumped. Obviously, the concentration of wells and of pumping draft in small areas makes it certain that the water will be "mined out" in those areas long before all the water in the reservoir could be removed at the current overall rate.

Concentration of wells is not the only factor to consider in predicting the length of time that water will continue to be available in any specific part of the area. The saturated thickness still remaining is of more concern than the thickness of material that has been unwatered. With development distributed as at present, the areas first to note "failing" water supplies probably will be those where the remaining saturated thickness is deficient and not necessarily those where pumping is concentrated excessively. Thus, the intensive pumping southeast of Plainview, Tex., has caused a notable depression in the water table, but the remaining saturated thickness still is about 150 feet. A short distance southeast, between Lockney and Floydada, the saturated thickness of the formation is very much less even though very little water is pumped there. South of Lubbock, Tex., the water level has fallen only slightly; yet there the Ogallala may be entirely unwatered in a few years because the saturated part of the formation is exceptionally thin.

Although the great bulk of water pumped has been taken from storage, it is known that there is some recharge from precipitation. Because this recharge occurs only in favorable areas, it follows that wells drilled in such places could approach a sustained perennial yield, even though the vast majority of wells in the Llano Estacado can have no such assurance. By far the greatest opportunities for infiltration and penetration of rainwater are in the sandy soils, and particularly in the sand dunes which are of wide extent in some parts of the Llano Estacado. Recharge of the ground-water reservoir in wet years is clearly recorded in wells in these sand-dune areas.

Pumping can increase the recharge to many ground-water reservoirs by vacating storage space which otherwise would at times be saturated to a level so high as to force rejection of some water that is available for recharge. Such conditions are rare in the Llano Esta-

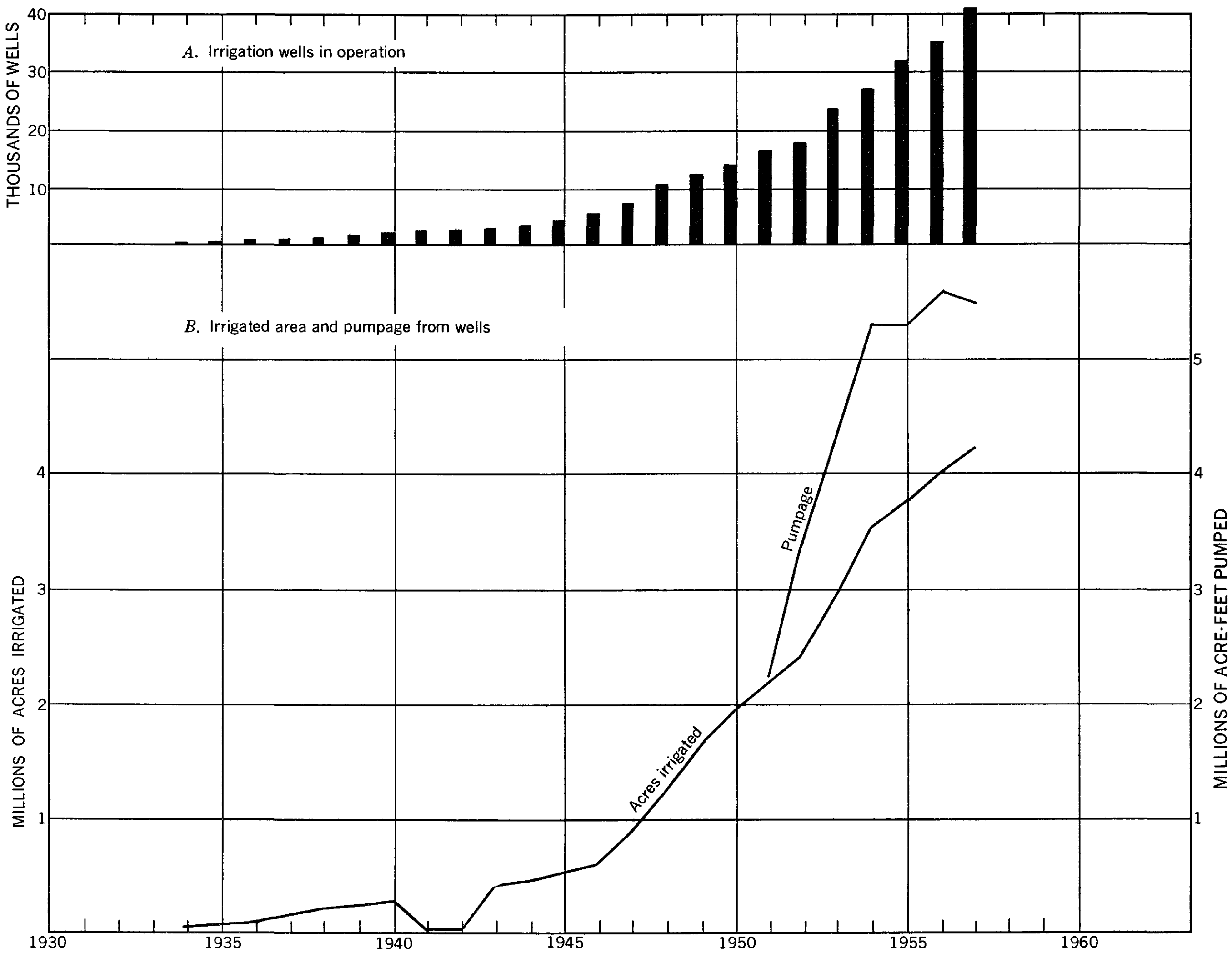

FIGURE 12.—Development and use of ground water in the Llano Estacado: number of irrigation wells, irrigated acreage, and pumpage from wells, 1934–57.

cado. Over most of the region the water table is more than 50 feet below the land surface, and the factor that limits recharge is not lack of storage space but the relative impermeability of materials beneath the land surface and the small amount of water available to penetrate below the soil zone. An exceptional area is that near Muleshoe, Tex. (fig. 13), where the water table was at shallow depth beneath sandy soil under natural conditions and has been so lowered by pumping as to create an opportunity for recharge from rainfall in the future. Also, in the Portales Valley, N. Mex., depressions which originally contained "water table" lakes are now excellent recharge areas when they receive inflow from exceptional rainstorms.

It may be possible to increase to some small extent the recharge to the ground-water reservoir by artificial means, although the water available for such recharge is small, especially when compared with the pumping draft. Water available for such recharge is that in depression ponds and—to a negligible degree—the intermittent flow of streams. After the depression ponds are filled with storm water, the water level generally drops rather rapidly at first, and then progressively more slowly. The more rapid decline of pond level when at high stage suggests that the materials underlying the pond margins are more permeable than those under the deepest part of the pond. Thus, contour trenches or other devices to divert and spread water before it reaches the deepest part of the depression might be effective in artificial recharge of the ground-water reservoir. Several attempts at artificial recharge through wells drilled in ponds have been only moderately successful at best, and it is evident that a foolproof technique for such recharge is still to be devised. Recent recharge through wells alternately recharged and pumped has apparently been fairly successful.

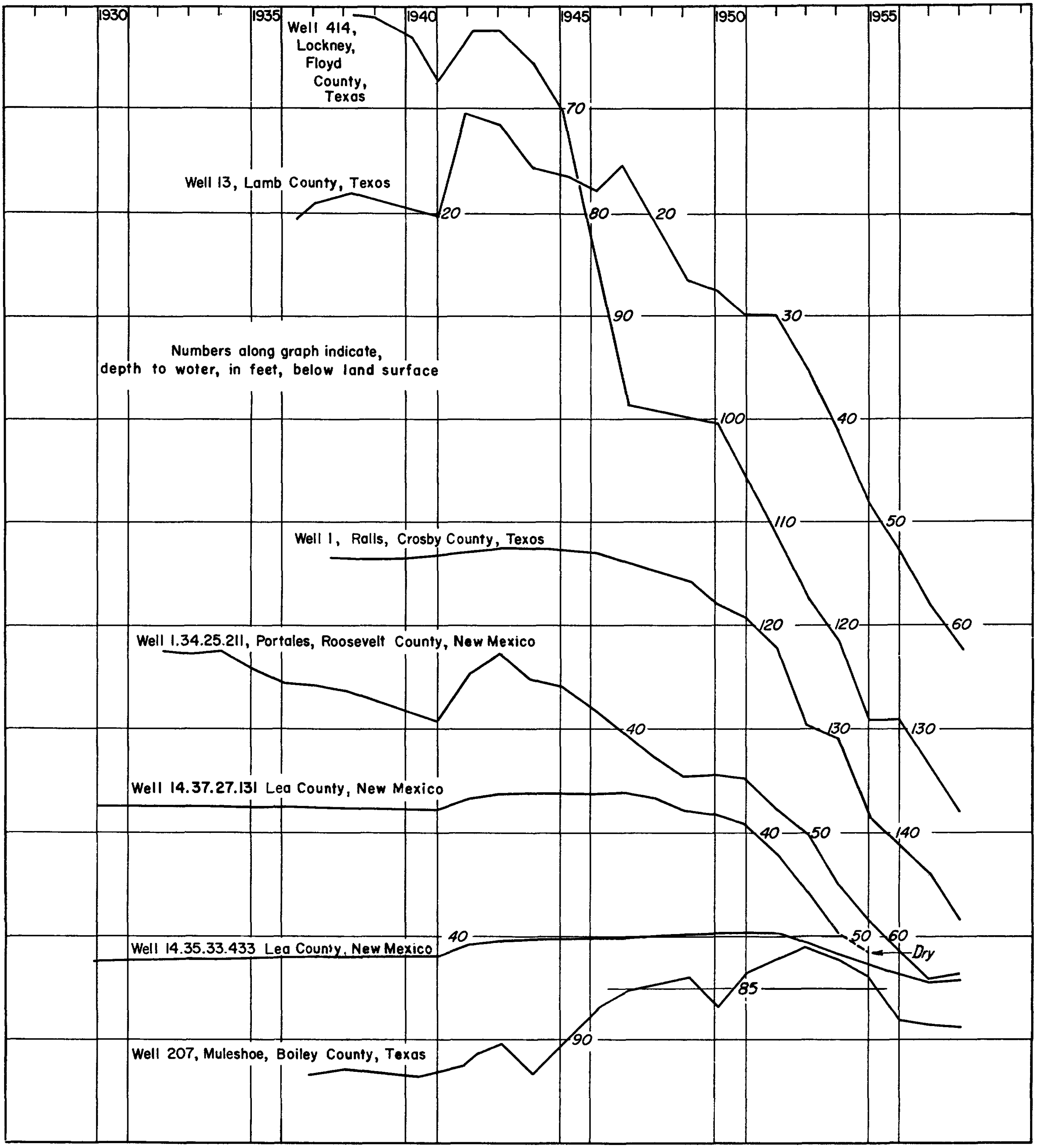

FIGURE 13.—Hydrographs of seven wells in the Llano Estacado, Tex. and N. Mex., 1930–57.

At some places it may be practical to augment the recharge to the ground-water reservoir by simple detention or spreading structures along stream channels, but the amount of water so conserved will be very small, as the runoff is small.

The declining trends of water level in the past suggest the means for most effective utilization of the ground-water reserves under the Llano Estracado—a pattern for distribution of wells and for rates of pumping that will assure the most efficient extraction of the water, and at the same time best serve the needs of the lands, municipalities, and industries dependent upon that water. By optimum spacing of wells, interference between them can be held within bounds so as to minimize pumping lifts and pumping costs. It is noteworthy that well spacing is a prominent part of the regulatory measures for ground-water development and use in both the Texas and New Mexico portions of the Llano Estacado, even though the two States are radically different in their legal concepts concerning rights to ground water.

The preceding discussion assumes that "mining" may continue until the ground-water reservoir is emptied, even though that can be done only by lifting the water as much as 500 feet at some places. It is recognized that the cost of pumping versus the value of resulting products is a controlling factor in the use of ground water; in many areas, cost would be the decisive factor. However, in the Llano Estacado there are three considerations that make predictions on this score inadvisable. First, there is no obvious alternate source of water sufficient to supply the present demand. Second, in parts of the irrigated area at least, oil and gas reserves are close at hand to provide sources of power so cheap that the cost standards of other regions do not apply. Third, any increases in cost of pumping may be offset in part by increases in efficiency of operation.

EFFECTS OF DROUGHT

Droughts appear to have little direct effect upon the ground-water reservoir of the Llano Estacado, which is the prime source of water for irrigation, industrial, and municipal supply. Studies by Theis (1937) indicate that replenishment to this reservoir in years of average precipitation—to say nothing of drought years—is negligible. Observable recharge occurs chiefly as a result of storms of unusual intensity and years of exceptionally abundant rainfall. Even in such wet years as 1941 the estimated recharge was barely equal to the aggregate discharge from wells in recent years.

The effect of recharge from precipitation in 1941 is shown in each of the hydrographs assembled in figure 13. Well 207, in the sandhills of Bailey County, Tex., is remote from large irrigation wells, but is in an area where ground water is readily recharged by precipitation, as shown by rises in water level during 1941–42, 1944–47, and 1950–52. In well 1.34.25.211 in the Portales Valley, N. Mex., the water level has trended downward in most years because of pumping, but this trend was reversed temporarily after the abundant precipitation of 1941, and was interrupted also in 1949 and 1950, when precipitation was greater than average. In well 14.37.27.131 in Lea County, N. Mex., the water level appears not to have been affected significantly by pumping until 1947; during the drought years 1933 to 1940 it declined less than half a foot, and then rose about 2 feet between 1941 and 1943 in response to recharge from the precipitation of 1941. Since 1947 the water-level decline has been caused chiefly by pumping, but it was less in 1949 and 1950—the years of greatest precipitation after 1941—than in other years.

Drought has had significant effects upon the development and use of water from wells, as shown by comparison of the graphs of figure 12. The rate of drilling of new wells was greater in the dry years 1953 and 1955 than in 1952 or 1954, when precipitation was nearer the long-term average. In the wet year 1942, which followed the wetter year 1941, fewer wells were drilled than in any other year since 1936.

The effect of drought upon annual pumpage is not easily illustrated, because of the very rapid expansion in irrigated acreage since 1943. It is known that pumping is likely to be reduced during years of exceptional rainfall, as for instance in 1941 and 1942, when little acreage was irrigated. During these years the water levels rose in most wells in the Llano Estacado, doubtless because of a combination of the circumstances of reduced pumping and significant recharge.

It may be concluded that in an aquifer such as the Ogallala formation of the Llano Estacado, where the volume of water in storage is many times the volume of average recharge per year and where it is replenished during infrequent wet periods, the effect of drought is negligible—being represented primarily by increased water usage. The problem is primarily how best to develop the water supply for maximum long-term extraction from storage with efficient use of the water.

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